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FINAL REPORT FOR
EVALUATION OF BERYLLIUM
FOR SPACE SHUTTLE COMPONENTS

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LMSC

SPACE SYSTEMS DIVISION

Prepared for National Aeronautics and Space Administration,
George C. Marshall Space Flight Center,
under Contract NAS 8-27739

LOCKHEED MISSILES & SPACE COMPANY, INC.
A   SUBSIDIARY   OF   LOCKHEED   AIRCRAFT   CORPORATION
SUNNYVALE, CALIFORNIA

FINAL REPORT

FOR

EVALUATION OF BERYLLIUM

FOR

SPACE SHUTTLE COMPONENTS
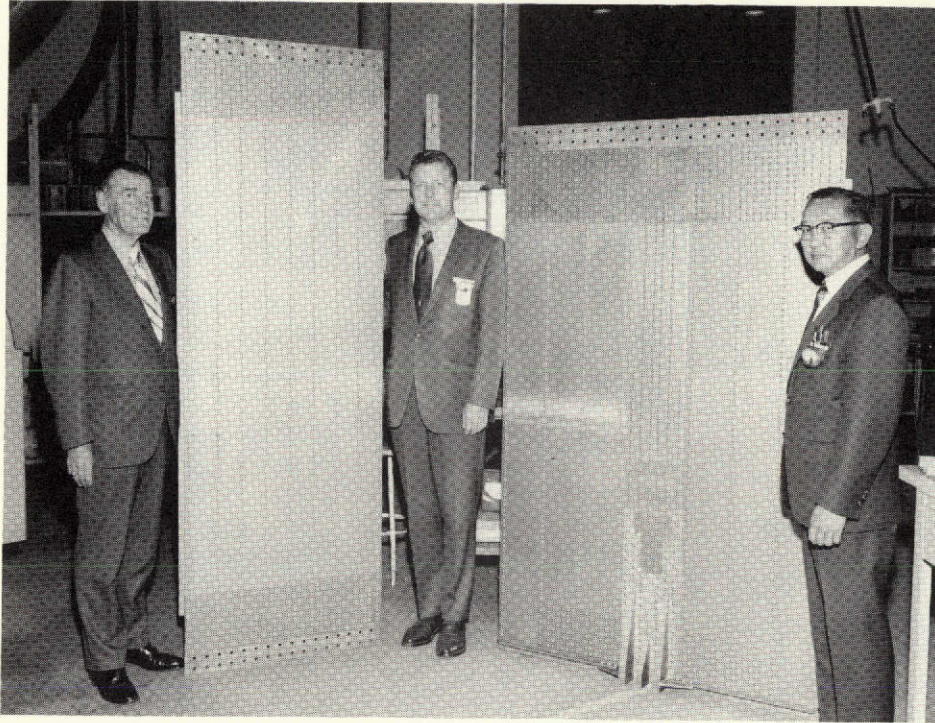
Contract NAS 8-27739

Prepared Under Direction of:

A. E. Trapp
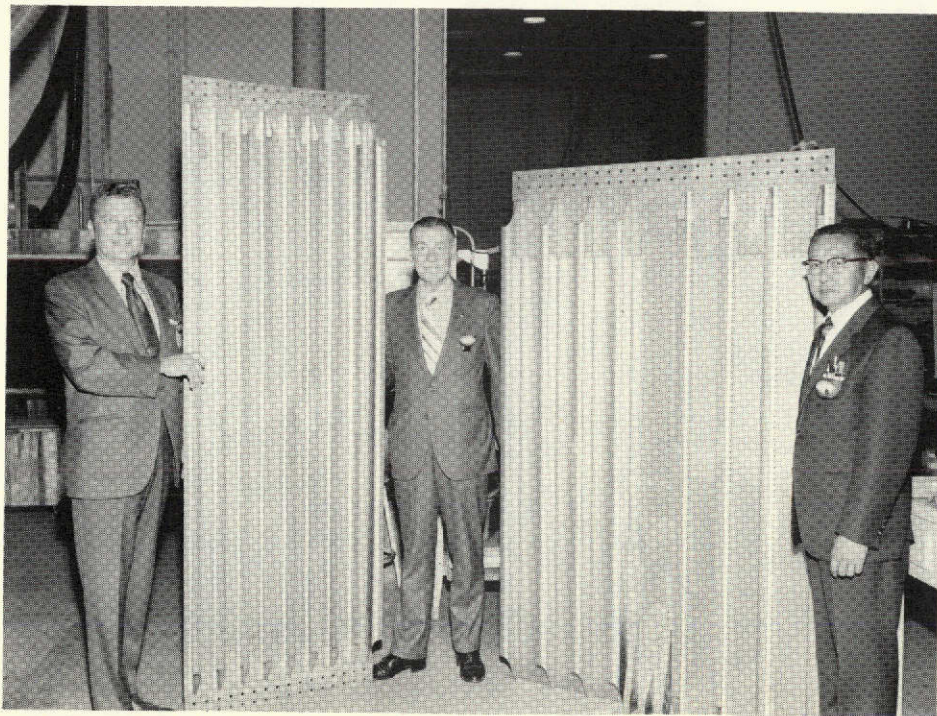Program Manager
Manned Space Programs

Approved by:

J. F. Milton
Assistant General Manager
Manned Space Programs

Prepared for George C. Marshall Space Flight Center by
Lockheed Missiles & Space Company, Manned Space Programs, Space Systems Division

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Delivered Panels — Front View

Delivered Panels — Reverse View

ABSTRACT

The primary objective of this program was to develop the required technology for application of beryllium to specific full-scale structural components and assemblies. This objective was accomplished by means of analysis, design, process development, manufacturing, and test. Also, material evaluations were conducted to check the mechanical properties of as-received material to gain design information on characteristics needed for the material in the Space Shuttle environment, and to obtain data needed for evaluating component and panel tests.

Four beryllium structural assemblies (a uniformly-loaded compression panel, a concentrated-load compression panel, a truss beam, and a shear beam — all typical of booster thrust-structure area) were analyzed and designed. Also, selected components of these assemblies, representing areas of critical loading or design/process uncertainty, were designed and successfully tested. In addition, two panel assemblies were fabricated for delivery to and test at NASA-MSFC. Trends in cost and weight factors were determined by progressive estimation at key points of preliminary design, final design, and fabrication to aid in a cost/weight evaluation of the use of beryllium.

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FOREWORD

This is the Final Report prepared by Lockheed Missiles & Space Company (LMSC) for NASA Contract NAS 8-27739, "Evaluation of Beryllium for Space Shuttle Components." Documented in this report are the LMSC efforts performed for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Alabama 35812, under the direction of Science and Engineering Directorate, Engineering Division, Structural Development Branch, Development Section. Mr. George R. Gerry, S&E-ASTN-ESD was the Contracting Officer's Representative (COR) for this program.

Program responsibility at LMSC was assigned to the Space Systems Division, Manned Space Programs, Structures Technology. Mr. A. E. Trapp was the LMSC Program Manager. Task Leaders for the five phases of the program were:

Phase I	– Materials Evaluation	– E. Willner
Phase II	– Design and Analysis	– G. S. Fuchigami/A. B. Burns
Phase III	– Process Technology Development	– S. H. Lee
Phase IV	– Fabrication	– E. W. Bauer
Phase V	– Test and Evaluation	– R. E. Mathiesen

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Section 1
INTRODUCTION AND SUMMARY

1.1 BACKGROUND AND OBJECTIVES

The primary objective of this program was to develop, refine, and document the required technology to demonstrate the feasibility of using beryllium for full-scale Space Shuttle components and assemblies. This was successfully accomplished by:

- Extending the range of beryllium material properties data to reflect Space Shuttle environments and structural design requirements
- Analyzing and designing specific structural assemblies under given loads and environments with a view to establishing minimum weight designs for shop production
- Developing and/or refining process techniques for fabrication and assembly which are applicable to a full-size Space Shuttle structure
- Applying the developed process techniques to the manufacture of the specified test articles and other required test components
- Conducting successful structural tests at LMSC on selected structural components, prior to the final panel tests at MSFC

The requirement for this program arose from the realization that a potential for major weight savings, weight control, and/or program cost reductions, exists through the proper use of advanced rather than conventional materials. For the Space Shuttle system, the ratio of gross liftoff weight to payload is very high with the payload weight approximately 1 percent of the total.

The control of design weight and weight growth, then, will be of paramount importance if system size and payload capability are to be maintained. In this regard, the use of advanced structural materials and concepts can be considered as a means of accomplishing this control. The successful realization of these benefits, of course, depends on the demonstration of the practical feasibility of such materials. The advanced material with the broadest hardware application, the most extensive background in characterization, and most unique all-around characteristics is beryllium.

1-1

Beryllium is a homogeneous and, effectively, an isotropic material that can, with confidence, be analyzed and designed within a convetional manner. It has the following advantageous properties for Space Shuttle application:

- High specific modulus — beneficial to stability-critical structures and generally to flutter, acoustic, and dynamic environments
- Elevated temperature capability — reduces insulation requirements
- High specific heat — absorption of heat lowers insulation requirements
- High thermal conductivity and dimensional stability — leads to low thermal gradients, stresses, and warpage

Beryllium also has excellent fatigue resistance and good strength. Because of its unique characteristics as a structural material, the use of beryllium in the Space Shuttle merits careful evaluation. If, in addition to its advantageous features, beryllium were as easy to work as aluminum, as ductile and as reasonable in costs as steel, it seems certain that almost all aerospace structural applications would involve this material. Unfortunately, this is not the case, and its reputation for high cost of material and manufacturing and brittleness has detracted from its use and from the recognition of the total system benefits available in terms of performance and/or cost. Where the value per pound of weight is drastically enhanced by a significant reuse capability, as in Space Shuttle, the employment of beryllium could not only decrease system size but also total program cost. The results of Space Shuttle design and beryllium applications studies performed by the Lockheed Missiles & Space Company (LMSC) and review activities by Bellcomm, Inc. (Refs. 1, 2, 3, and 4), indicate that major weight reductions can be realized and potential program cost reductions can be attained through the use of beryllium instead of conventional materials, even with a manufacturing complexity factor of greater than three when compared to aluminum.

The cost issue, then, has a basic dependence on material and fabrication. Since material price varies widely with sheet thickness or gage, and development prices involved in developing extruded or forged shapes, the cost-effective measure or the greatest structural efficiency may not provide an "optimum" structure, (where a

built-up "box" strut may replace a homogeneous continuous tube). Manufacturing cost is also greatly influenced by the fabrication processes necessary to safely produce a sound structure, such as:

- Chemical etching after all metal removal
- Drilling matching holes when required
- Care in drilling and machining
- Prevention of beryllium products from escaping during fabrication processes
- Close tolerances to avoid "fit-up" stresses

Gain in cost must be counterbalanced by system performance benefits. As reported, the increased cost due to beryllium use in the panels fabricated for this program indicates a manufacturing complexity factor of less than three, and that the cost per pound is well within a cost effectiveness value per pound for the Space Shuttle.

Assuming, then, that the use of beryllium can be proven cost effective, the successful effort initiated by this program has provided limited reliable results of sufficient depth to demonstrate that far more serious consideration be given to its use. The structures developed and tested demonstrate that complex structures can be designed, fabricated, and assembled from beryllium material with full confidence in the capability of the finished product.

1.2 PROGRAM PLAN

As previously stated, the primary objective of this program was to develop the required technology for application of beryllium to specific full-scale structural components and assemblies. This objective was accomplished by means of analysis, design, process development, manufacturing, and test. Also, material evaluations were conducted to check the mechanical properties of as-received material to gain design information on characteristics needed for the material in the Space Shuttle environment, and to obtain data needed for evaluating component and panel tests.

1-3

Four beryllium structural assemblies (a uniformly-loaded compression panel, a concentrated-load compression panel, a truss beam, and a shear beam – all typical of booster thrust-structure area) were analyzed and designed. Also, selected components of these assemblies, representing areas of critical loading or design/process uncertainty, were designed and successfully tested. In addition, two panel assemblies were fabricated for delivery to and test at NASA-MSFC. Trends in cost and weight factors were determined by progressive estimation at key points of preliminary design, final design, and fabrication to aid in a cost/weight evaluation of the use of beryllium.

To provide background and perspective, a summary of Lockheed's development of the beryllium evaluation program is contained in the following paragraphs and illustrated in Fig. 1.2-1.

1.2.1 Phase I – Materials Evaluation

In this phase, fundamental material characteristics, needed to gain confidence in the successful verification of the structure by test, were generated – either by extrapolation from available data or by specimen tests. For the design phase, heavy reliance was placed on data trends and procedures developed in previous Lockheed work. Although chemical composition, tension properties, and elongation characteristics for the high-elongation material to be used were obtained from the supplier, the mechanical properties received a verification check to obtain a consistent set of data. Properties needed to provide design data and evaluation data for panel tests were emphasized, particularly for those gages of material for which data are relatively scarce (thicknesses in cross-rolled sheet 0.100 in. and greater). Full identification and traceability of each test specimen, with respect to the as-received parent-sheet stock, was maintained. The results of this task provided essential information for Phases II, III, and V.

1.2.2 Phase II – Design and Analysis

Based on the specified guidelines, the selected panels and components were laid out and detail-designed to utilize primarily beryllium. The designs resulted in drawings

ESTABLISH PLAN FOR

● PROCESS TECHNOLOGY
  DEVELOPMENT

● FABRICATION

DEVELOP PROCESS TECHNOLOGY

● FORMING
● JOINING
● ASSEMBLY
● PROD. DESIGN METHODS

DEVELOP BERYLLIUM MECHANI-
CAL PROPERTIES DATA FROM
AS-RECEIVED MATERIAL

FINAL REPORT

NASA REVIEW
& APPROVAL

PERFORM PRE-DESIGN
ANALYSIS OF STRUCTURAL
COMPONENTS/PANELS

● MAT'L/WEIGHT
  OPTIMIZATION
● STRENGTH

COMPLETE
STRUCTURAL
DESIGN AND
ANALYSIS

FABRICATE
STRUCTURAL ASSEMBLIES

COMPO-NENTS	PANELS

TEST STRUCTURAL
ASSEMBLIES AT
NASA/MSFC

PERFORM COMPONENT
STRUCTURAL TESTS AT
LOCKHEED

STRUCTURAL TEST
PLANNING FOR
TESTS AT NASA/MSFC

PROVIDE
TEST SUPPORT
AT NASA/MSFC

Fig. 1.2-1 Program Approach — Evaluation of Beryllium for Space Shuttle Components

consistent with the mechanical properties developed and substantiated in Phase I and the processing requirements of Phase III. Representative environmental information has been developed and a structural evaluation conducted to verify the capability of the structure to withstand the specified loadings. The designs consider material/size availability to maintain reasonable costs and have been thoroughly analyzed with the help of such computer programs as STAGS and REXBAT. A selection of components for test at Lockheed has been made, and a progressive detail weight summary developed for the four basic structural assembly designs at the significant key points of conceptual design, release, and final assembly (where applicable) to provide information on weight trends and nonoptimum factors for this type of beryllium construction. This task provided essential information for Phases III, IV, and V.

1.2.3 Phase III — Process Technology

Although proven experience exists at Lockheed for the production expertise required for the manufacture of significant beryllium structural components, the refinement and extension of present techniques to the large structural components of Space Shuttle required an effort to determine the most efficient and feasible techniques. Areas of forming, machining, joining, tooling, and assembly were examined to project the techniques necessary to construct the candidate structures. The refined techniques were well documented to provide a basis for evaluation of unforeseen or unique problem areas.

An evaluation plan was developed, with the concurrence of NASA, to define the details of Phases III and IV to be investigated, their depth, and key dates, so that information and hardware were available when needed for Phases II and IV.

1.2.4 Phase IV — Fabrication

Based on inputs from Phases II and III, selected test components and the required compression panels were constructed under this task. Tooling, metalworking, and assembly took place primarily in the Lockheed Beryllium Facility in Building 170.

Forming tools were fabricated from appropriate materials to obtain a compatible coefficient of expansion with beryllium and to minimize oxidation. Existing facilities and techniques were generally adequate for this task, which provided information feedback for Phase III and hardware components for Phase V.

To provide cost trends for this type of beryllium construction, progressive fabrication estimates were developed or accumulated and documented at the key points of conceptual design, design release, and throughout fabrication. These data provide the basis for cost projection of the truss and shear beams, considering the methods and techniques to be employed in a production-type atmosphere.

1.2.5 Phase V — Test and Evaluation

This phase was composed of two separate regimes — component development testing (to gain confidence in design details for the full-scale hardware) and panel assembly testing (to verify the specified structural capability). The component tests were conducted successfully in Lockheed facilities under representative heating and loading conditions. A test plan was prepared by Lockheed for the panel assembly tests to be conducted at NASA-MSFC. This test plan specified loading and temperature sequencing, instrumentation type and location, data requirements, post-test failure appraisal, and documentation. LMSC will supply on-site test personnel at MSFC for the purpose of test monitoring, integration, and preliminary evaluation of final test results. A final test evaluation will be prepared by Lockheed and will contain an examination of the failure modes, a comparison of analytical and test results, and conclusions and recommendations.

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Section 2

TECHNICAL DISCUSSION

2.1 PHASE I — MATERIALS EVALUATION

The major objective for this segment of the program was to make those determinations necessary to establish confidence in analysis for the mechanical behavior of specific components. The effort was directed to accurately determine the following:

- Tensile yield strength, ultimate tensile strength, percent elongation, and compression yield strength for both longitudinal and transverse directions at room temperature, 425°K $(300^{\circ}$F) and 592°K $(600^{\circ}$F)

- Creep strengths for 100 hour exposure to 425°K $(300^{\circ}$F) and 592°K $(600^{\circ}$F)

- Creep strain on cyclic mission profile thermal exposure from room temperature to 592°K $(600^{\circ}$F)

- Room temperature fracture toughness

- Precision modulus of elasticity at room temperature

- Fatigue strength at room temperature

- Three point bend testing for both longitudinal and transverse directions at room temperature, 425°K $(300^{\circ}$F) and 592°K $(600^{\circ}$F)

- Charpy-V notch impact strength at room temperature, 425°K $(300^{\circ}$F) and 592°K $(600^{\circ}$F)

Complete test data, including metallography and detailed description, are reported in EM B1-M1-3 (Appendix C) and discussed in summary form in this section.

Tension and compression data were statistically analyzed for interpretation as Military Handbook 5-type properties.

2.1.1 Test Material

Beryllium sheet used in this program was procured to meet all requirements of LMSC Material Specification LAC-07-4008A. Kawecki-Berylco Company (KBI)

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furnished sheets produced from three different pressings (for clarity, the source for a given sheet is the "pressing". The expression "heat" will have no significance herein except as parenthetically noted under "Producer's Identity" in the tables of test data).

KBI has certified the chemistry for each pressing and the analyses of each are tabulated in Table 1, Appendix C. The chemistry met requirements of LAC 07-4008A.

A total of 15 cross-rolled beryllium sheets were produced from the three pressings. Five sheets of 0.315 cm (0.124-in.) thickness were made from pressing 379P, four sheets of 0.3556-cm (0.140 in.) thickness from pressing 395P, and six sheets of 0.3556-cm (0.140-in.) thickness from pressing 432P. Table 2, Appendix C, lists the KBI data for room temperature tensile properties. These properties meet the mechanical property requirements of LAC 07-4008A. Three sheets from each pressing were selected at random for the materials evaluation.

2.1.2 Specimens

Specimen Layout. EM B1-M4-2 (Appendix Q) illustrates the utilization of the beryllium sheets. Figure 2-1 in Appendix Q illustrates the specimen layout for removal of coupon specimens from a sheet.

Specimen Codification. Table 2.1-3 in EM B1-M1-2 (Appendix B) illustrates the method used to identify each specimen for a given test.

Specimen Configurations. EM B1-M1-2 (Appendix B) illustrates details of specimen configuration. The following procedures were included in preparation of specimen:

- Etch 0.0127-cm (0.005-in.) per side, including shoulders as well as reduced sections
- Use 0.00254-cm (0.001 to 0.002-in.) taper from ends to center of tensile specimens

Specimen Selection for Test Program. Because of limited funding and the desire to provide maximum useful engineering data, the original program layout was modified slightly to more clearly quantify elevated temperature properties. Included in this change was a relaxation of some previously prescribed room temperature tests. Sufficient room temperature tensile testing was performed to corroborate KBI tensile data received for all sheets. Sufficient confidence for room temperature compression yield strengths was established to provide for additional elevated temperature compression test data. Additional creep-strain testing was performed to enhance evaluation and, similarly, additional thermal cycling creep-strain exposures were undertaken. Modulus was determined for the longitudinal orientation for one sheet from each of the three pressings. All the charpy-V notch, fracture toughness, and three-point bend specimens previously prescribed were evaluated. Photomicrographs have been made in the longitudinal and transverse directions for a representative sheet from each of the three pressings.

2.1.3 Test and Analysis

Tensile Tests. An outline of those tensile tests made for this program at LMSC is presented in EM B1-M1-3, Appendix C, Table 3. Tensile data and typical load strain curves obtained are also presented in Appendix C.

All tensile tests for determining yield strength, tensile strength, and elongation were made in a 10,000-lb capacity Instron testing machine utilizing two Wiedmann Baldwin lightweight type 2-M extensometers assembled as one extensometer and wired electrically to average strain on opposite edges of the specimen.

The tensile properties at 425°K (300°F) and 592°K (600°F) were determined in accordance with ASTM recommended test procedure E21-70 using a Marshall resistance heated furnace controlled to 1.668°K ($\pm3^{\circ}$F) and a Microformer extenso-meter, Model PSH-8MS. Typical tensile tested specimens are shown in Fig. 2.1-1.

Results of the statistical analysis for program data are presented in Table 2.1-1 as Military Handbook-5 Type A and B values. Good agreement is shown for the tensile ultimate properties at room temperature; however, A and B values for tensile yield strength are shown to be about 6 percent lower than current Military Handbook-5 minimums. A correlation of tensile property behavior for iron to aluminum chemistry also appears.

Compression Tests. The compression yield strengths for this program are outlined in Table 8 in EM B1-M1-3, Appendix C. Typical compression-tested specimens are shown in Fig. 2.1-2. Compression data and typical load strain curves are shown in Appendix C.

Compression tests were accomplished by techniques previously used. Specimens were supported by means of a spring-loaded stainless steel jig; the test setup is shown in Fig. 2.1-3. Strain was measured electrically on the edges of the center 2.54-cm (1 in.) of the specimen using two Wiedemann-Baldwin Model T2-M extenso-meters wired to average strain from opposite sides of the specimen. Resistance heating of Rene' 41 platens, fixturing and specimen, was employed for the elevated temperature testing; control of temperature was $\pm 1.668^{\circ}$K (3°F).

Figures 17 through 20 of Appendix C reveal A and B value compression behavior, typical of Military Handbook-5 methods, for analysis of pressing to pressing over the range of test temperatures. A correlation of compression data for iron to aluminum chemistry also appears. Table 2.1-1 also contains A and B values for compression yield strength.

Creep-Strain Testing. When this program began, creep-strain equipment at LMSC had been committed to other activities. Consequently, the constant load creep-strain testing was performed by the Joliet Metallurgical Laboratories (JML), Joliet, Illinois, under the direction of LMSC. The test specimen was designed to conform with the JML test configuration shown in Appendix B. Averaging dial gage indicators, accurate to 0.00254-cm (0.001 in.), were assembled with extensometer prior to loading. Marshall furnaces were used for heating and were controlled to within 1.668°K (3°F). Standard practice of incremental loading was used. Figure 2.1-4 illustrates the test setup.
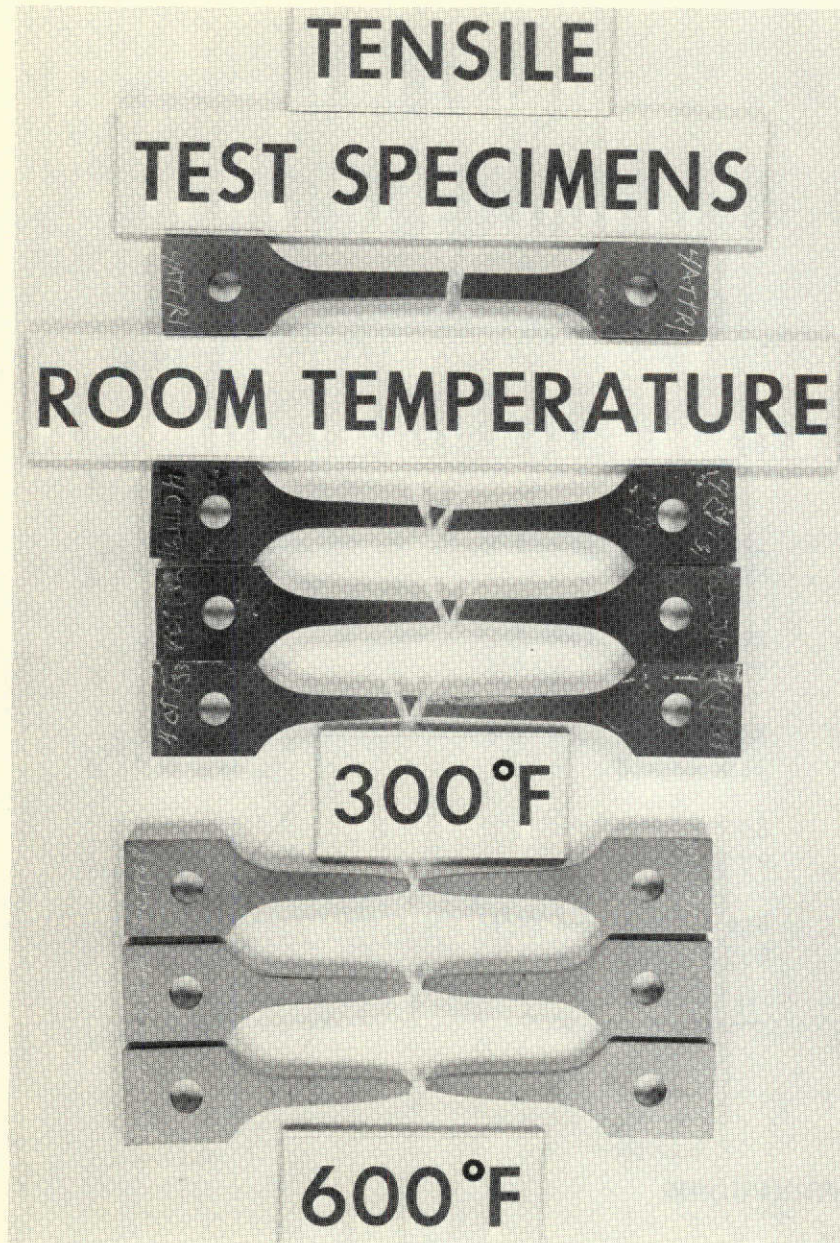
Fig. 2.1-1 Typical Tensile Tested Specimens
Versus Temperature
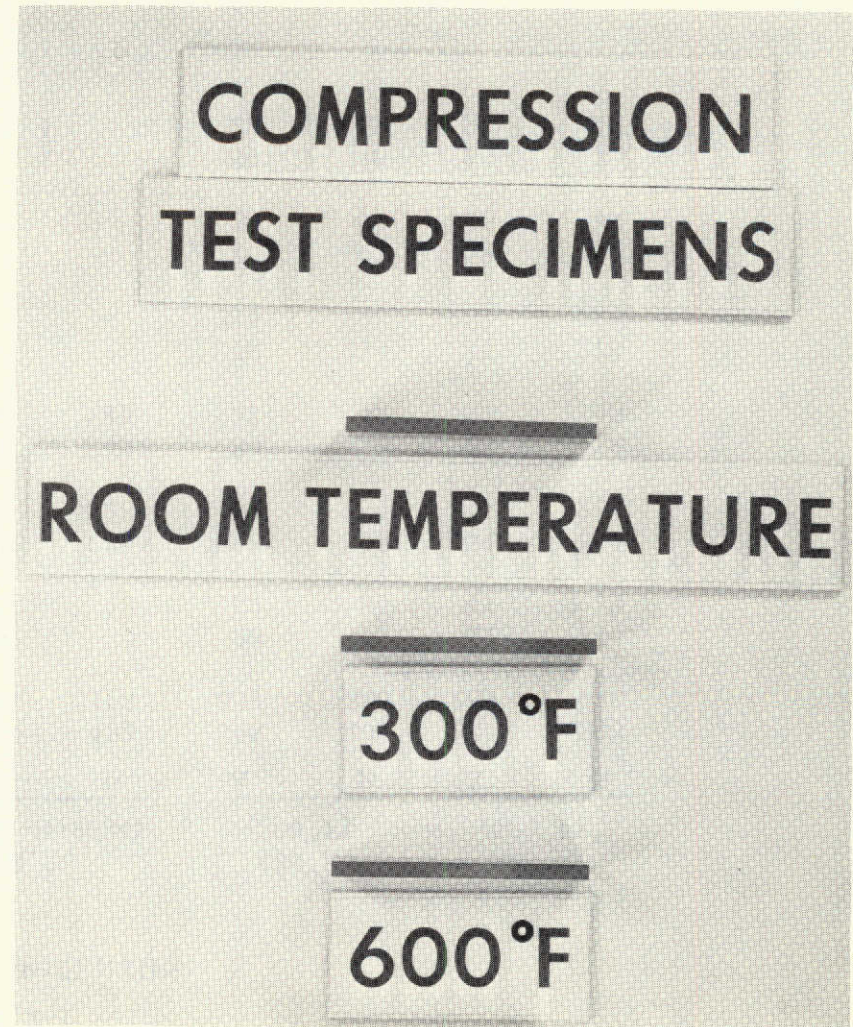
Fig. 2.1-2 Typical Compression Tested Specimens
Versus Temperature

Table 2.1-1

MECHANICAL PROPERTIES

Property		R.T.		R.T. (MIL-B-8694)		425^OK $(300^O$F)		592^OK $(600^O$F)	
		A	B	A	B	A	B	A	B
F_{tu}, M N/m^2	L	441	469	448	483	386	407	283	296
	LT	455	476	448	483	503	586	283	296
F_{tu}, ksi	L	64	68	65	70	56	59	41	43
	LT	66	69	65	70	53	56	41	43
F_{ty}, M N/m^2	L	276	317	296	338	248	290	234	262
	LT	276	324	296	338	255	296	214	241
F_{ty}, ksi	L	40	46	43	49	36	42	34	38
	LT	40	47	43	49	37	43	31	35
F_{cy}, M N/m^2	L	303	338	–	–	276	310	262	276
	LT	310	345	–	–	248	290	207	228
F_{cy}, ksi	L	44	49	–	–	40	45	38	40
	LT	45	50	–	–	36	42	30	33
E_{Long}, % in 2.54 cm (% in 1 in.)	L	–	5	4		36	45	60	64
	LT	–	6	4		27	35	27	35
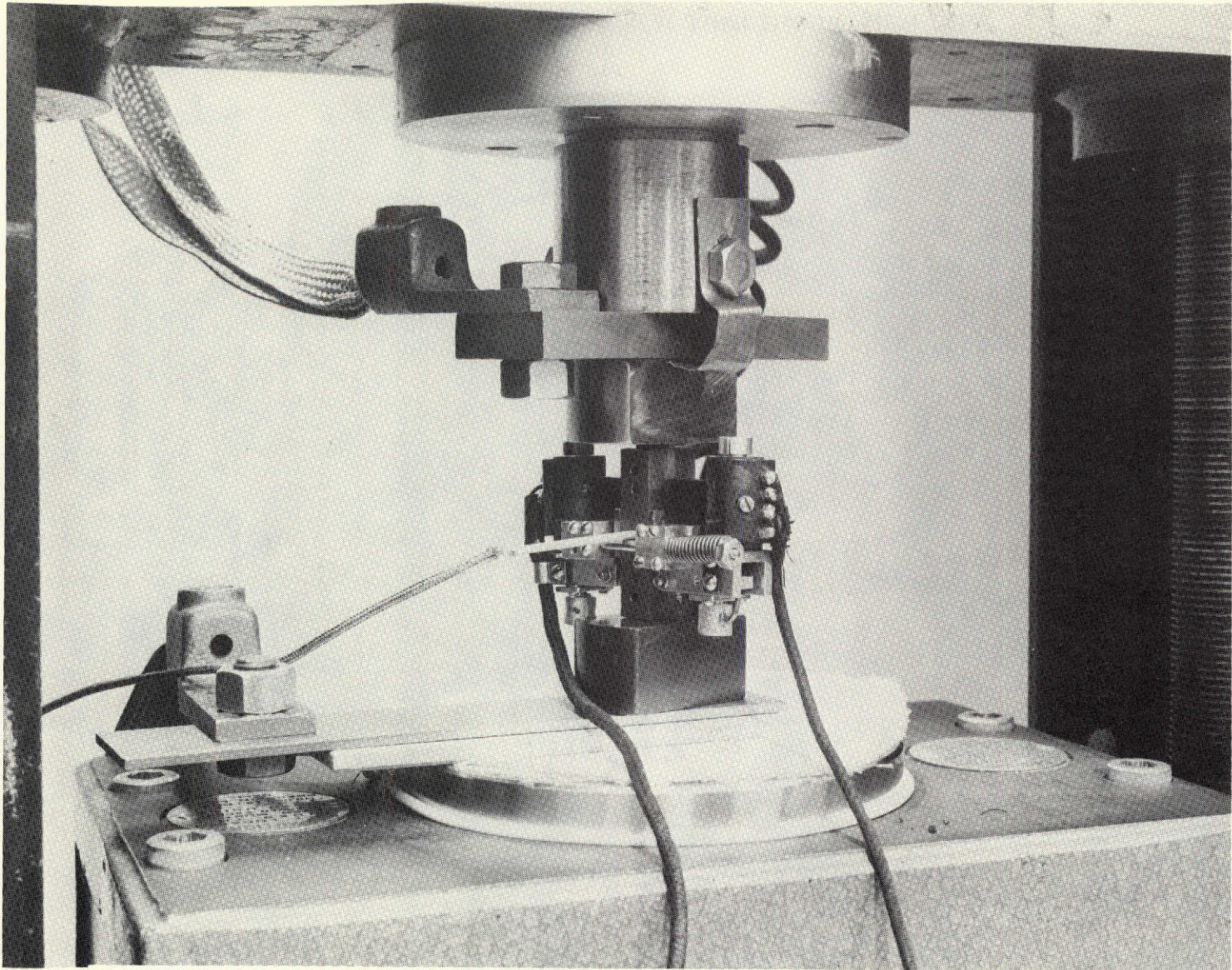
Fig. 2.1-3 Compression Test Setup
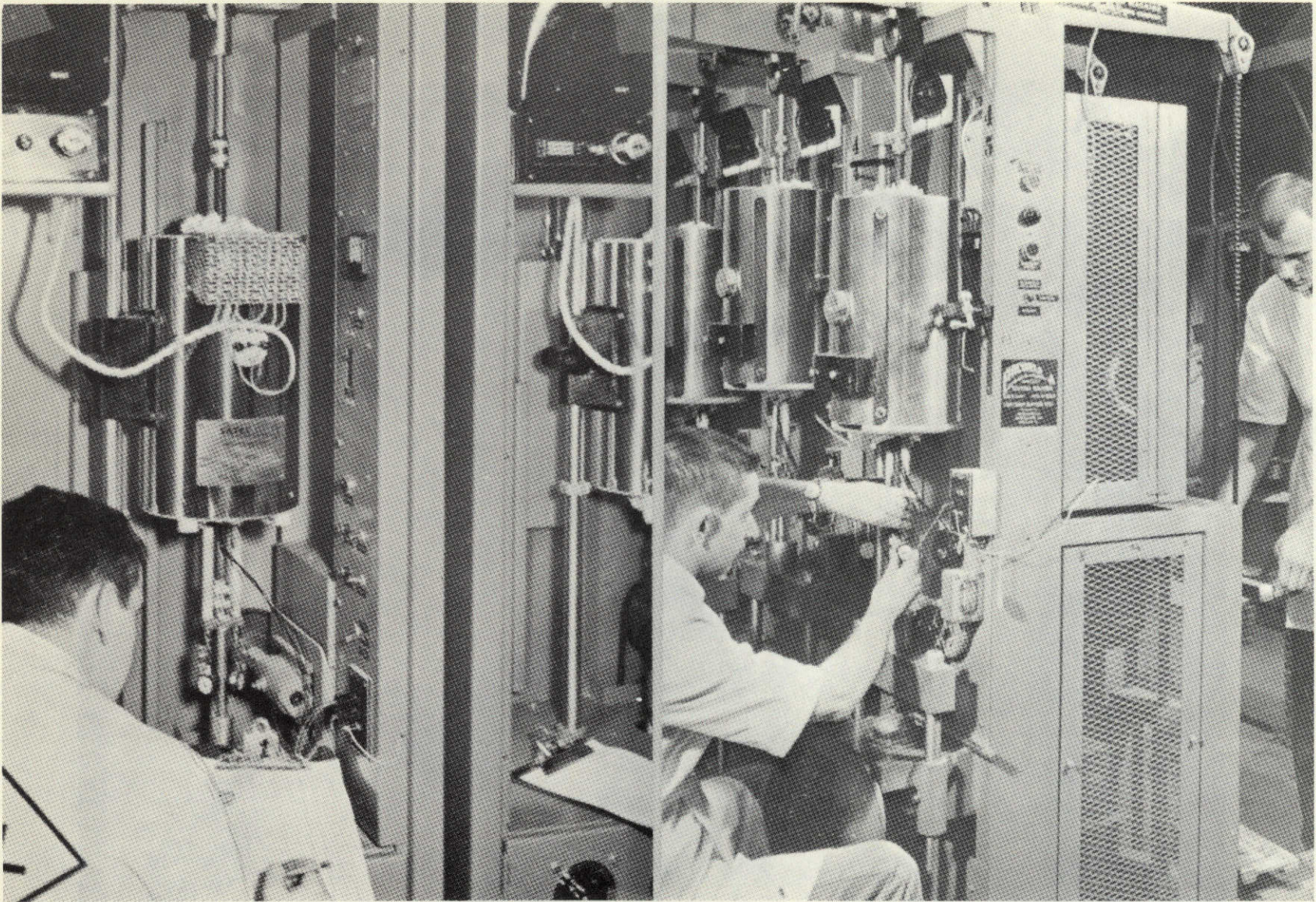
Fig. 2.1-4 Creep Testing Setup at Joliet Metallurgical Labs

Figure 22 of Appendix C is a plot of the 100-hr creep strain for the two sheets at 425°K (300°F) and 593°K (600°F). Because of the large scatter, no sensible strain rate plot can be presented. This scatter is considered normal for creep testing. Additional specimens would be required to develop a meaningful analysis. Figure 2.1-5 illustrates two typical stressed creep-strain specimens.

Creep Strain on Thermal Cycling. One specimen was subjected to 25 cycles of thermal excursions from room temperature to 592°K (600°F) with rate maintained uniformly so that peak temperature was reached in three minutes. The specimen was loaded to a stress of 20,000 N/cm^2 (29,000 psi). Permanent strain was measured after five cycles, followed by two 10-cycle exposures. Total strain or permanent set was measured, in contrast to the plastic component measured during the 100-hr creep strain tests. Apparently, the specimen underwent the major percentage of creep within the first five thermal cycles. Strain of 0.118 percent occurred after the first five cycles with but a maximum addition of 0.003 percent strain on subsequent thermal cycling. Figure 2.1-6 illustrates the test specimen.

Fracture Toughness. Part-through-the-thickness surface flaws were Eloxed, followed by chem-etching. Precracking of the specimens by means of fatiguing proved to be a difficult process. Previous experience indicated optimum conditions for precracking would be at 705°K (800°F) for cyclically loading within prescribed limits. Unfortunately, this process consumed a disproportionate amount of time. A decision was made to mechanically damage the root of the notch by means of a sharp-edged tool. Using Irwin's analysis for calculating fracture toughness, sheet H1510 with the flaw normal to the transverse direction, the fatigued precracked K has been calculated to be approximately 11,000 N/cm^2 $\sqrt{cm}$ (10,000 psi $\sqrt{in.}$). This is in contrast to the small differentials for the mechanically damaged flaw which indicated calculated K from 16,170 to 18,260 N/cm^2 $\sqrt{cm}$ (14,700 to 16,600 psi $\sqrt{in.}$) for the balance of tests. Figures 2.1-7 and 2.1-8 illustrate the specimen fracture features. Specimens 2ATKR4 and 5 reveal very little fatigue growth. It was con-jectured that fatigue at 705°K (800°F) developed a plastic zone ahead of the flaw which in turn would provide for higher fracture toughness, which was not observed. Secondly,

CREEP-STRAIN
TEST SPECIMENS

300°F Specimen 4AlS32 Stressed 48KSI on Loading.
Strained 9 Percent on 100 Hours of Load
Longitudinal Orientation Sheet H1535-432P
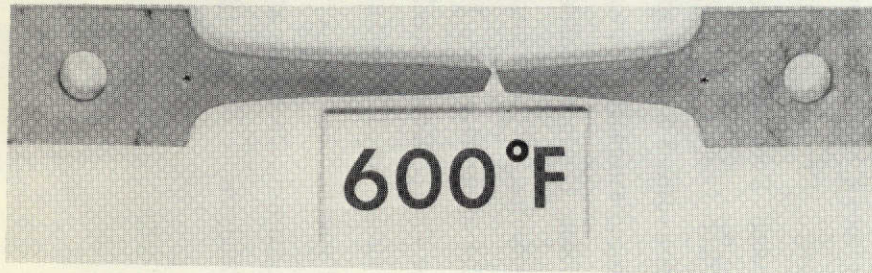
600°F Specimen 2Al566 Stressed 50 KSI on Loading.
Failed on Loading Longitudinal Orientation
Sheet H1510-379P

Fig. 2.1-5 Typical Creep Specimens

THERMALLY CYCLED
CREEP-STRAIN
TEST SPECIMENS
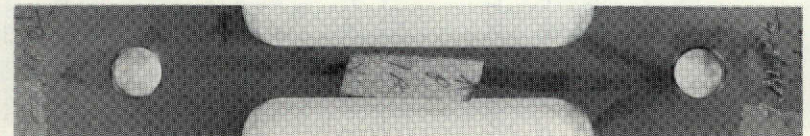
2A LPI Longitudinal Orientation Sheet H1510-379P
Stressed 29KSI on Loading Thermally Cycled to
600°F From R.T. in 3 Minutes, 25 Cycles, Total
Strain 0.115 Percent

Fig. 2.1-6 Thermally Cycled Creep-Strain Specimen
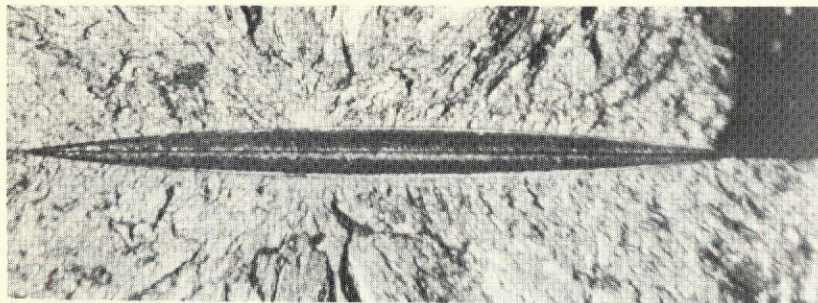
Specimen: 2ALKR3; $a_0 = 0.021$ in., $c_0 = 0.261$ in.
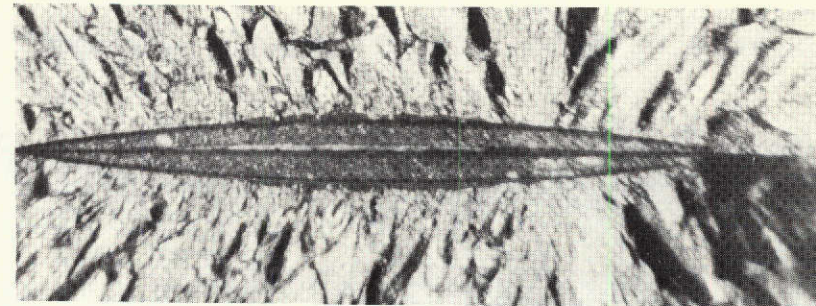
Specimen: 2ATKR6; $a_0 = 0.029$ in., $c_0 = 0.259$ in.
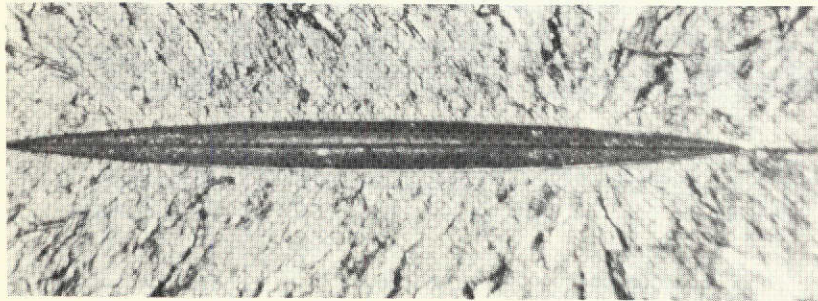
Specimen: 2ALKR2; $a_0 = 0.019$ in.; $c_0 = 0.278$ in.
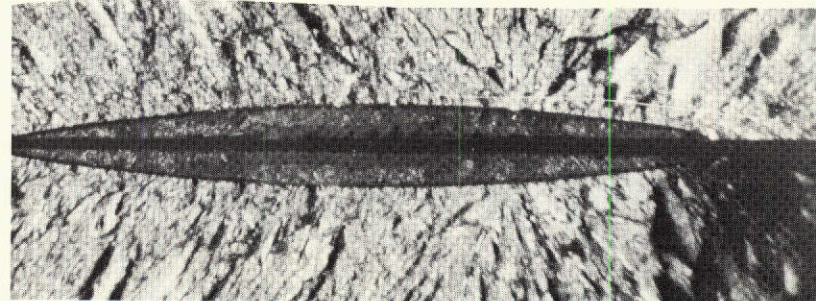
Specimen: 2ATKR5; $a_0 = 0.028$ in., $c_0 = 0.265$ in.
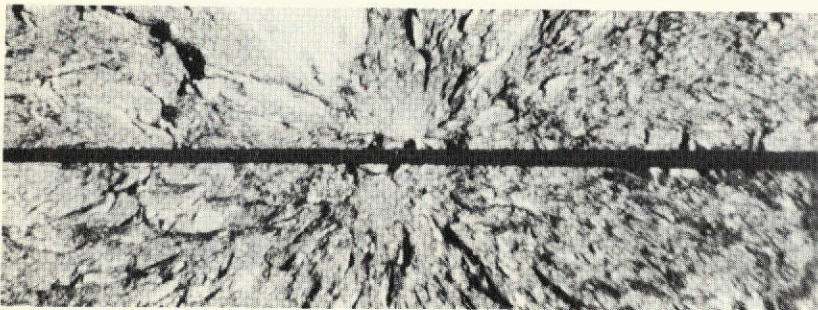
Specimen: 2ALKR1; $a_0 = 0.010$ in.; $2 c_0 = 0.035$ in. Specimen: 2ATKR4; $a_0 = 0.022$ in.; $c_0 = 0.263$ in.
SH: H1510-3790
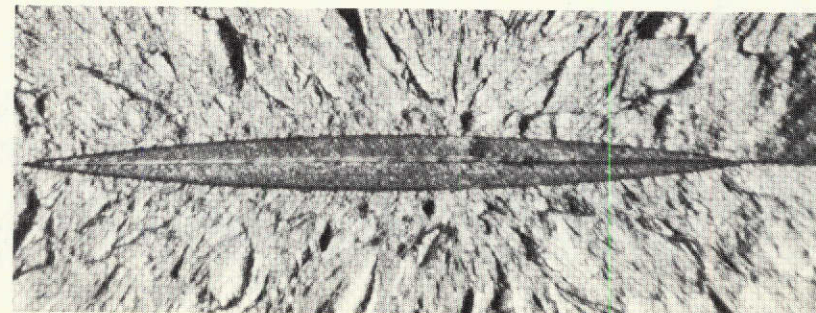
Fig. 2.1-7 Fracture Features of Fracture Specimens
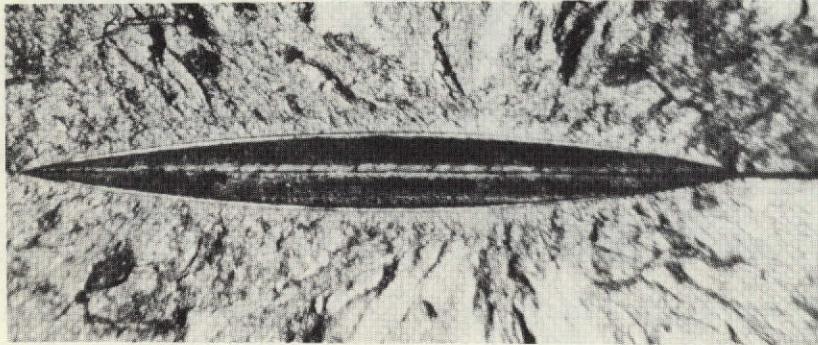
Specimen: 4ALKR2; a_o = 0.030 in., c_o = 0.265 in.
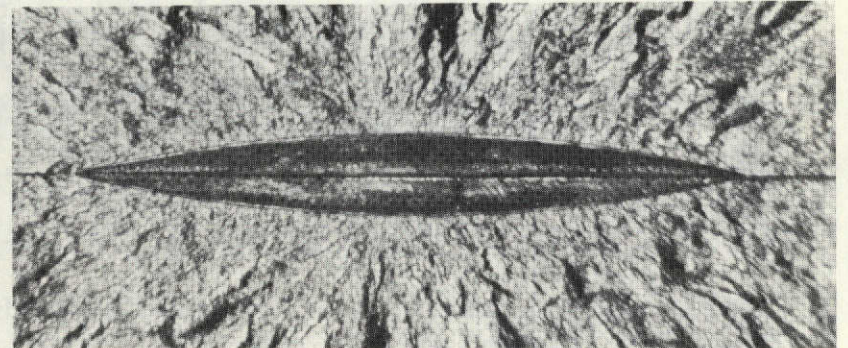
Specimen: 4ATKR4; a_o = 0.031 in., c_o = 0.246 in.
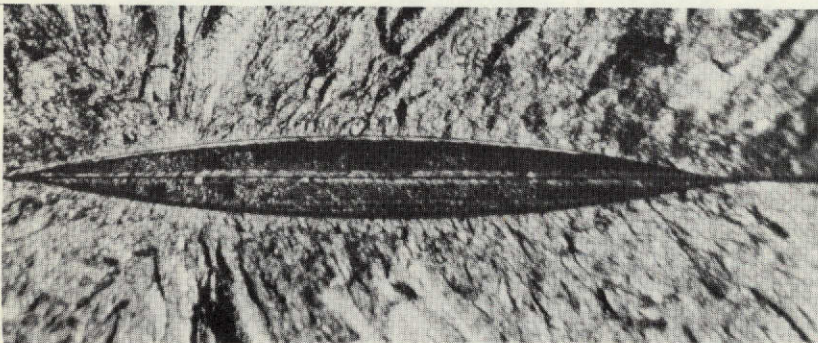
Specimen: 4ALKR1; a_o = 0.032 in., c_o = 0.257 in.
SH: H1535-432P
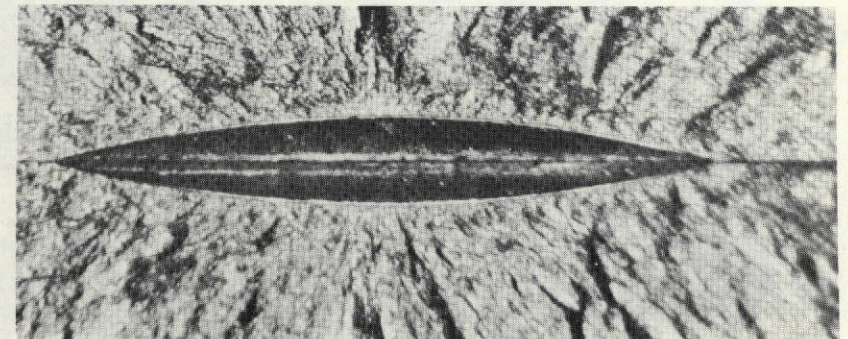
Specimen: 4ATKR3; a_o = 0.032 in., c_o = 0.224 in.

Fig. 2.1-8 Fracture Features of Fracture Specimens

the mechanically damaged twinned structure would theoretically have lower fracture toughness than calculated because the depth of twinned structure was not added to the depth dimension "a" for calculation of "K". Consequently, at this time it appears that (1) evaluation of K is dependent upon method of creating the flaw, and (2) the data may be interpreted as valid for application to flaws or imperfections created by means of similar processing histories. Figure 2.1-9 illustrates a typical surface flawed fracture specimen.

Young's Modulus of Elasticity. Data for the precision modulus of elasticity is shown in Table 12 of Appendix C. The specimens were prestrained prior to strain gaging in addition to straining with strain gages installed before commencement of strain readings for determination of modulus. Micromeasurement strain gages model EA 06-250BG-120 for a 0.635 cm (0.25-inch) gage length were applied with Eastman 910 adhesive. Full bridge averaging of two strain gages were used to enhance accuracy. Data were not confirmed by means of Tuckerman optical strain gage techniques. A typical specimen is shown in Fig. 2.1-10.

Fatigue Testing. Fatigue testing was performed in a constant amplitude 4540 Kg (10 kip) resonant-fatigue Lockheed-designed machine at frequencies ranging from 2015 to 2475 cpm and at a stress range ratio of + 0.1. Each test data point was plotted on a working curve, and testing was concluded when the fatigue properties were reasonably defined.

Figures 23 and 24 of Appendix C graphically illustrate the stress to number of cycles of test for endurance limits. Figure 2.1-11 illustrates a typical fractured fatigue specimen.

Three Point Bending. Load was applied through 0.475 cm (0.187 in.) radius dowels using a constant cross-head rate of 0.127 cm (0.05 in.) min. Displacements of the cross-head on the Riehle testing machine were autographically measured with a microformer deflectometer and recorder within 0.00254 cm (0.001 in.) of deflection measurements made at the center of the span measured by means of a dial gage. Heating of the specimens was in a Marshall furnace controlled to $\pm 1.668^{\circ}K$ ($3^{\circ}F$).

FRACTURE TOUGHNESS
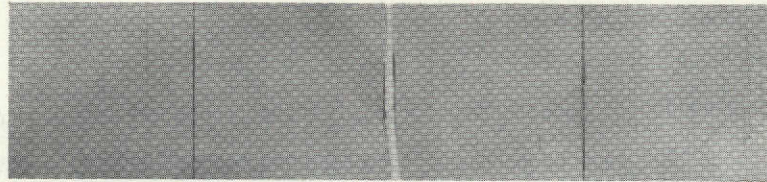
ROOM TEMPERATURE

Fig. 2.1-9 Fracture Toughness, Typical Surface Flawed Specimen

ELASTIC MODULUS
TEST SPECIMENS
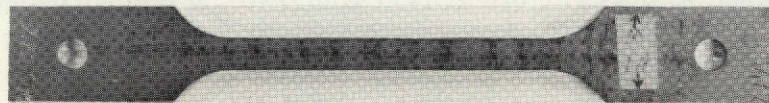
ROOM TEMPERATURE

Fig. 2.1-10 Precision Elastic Modulus Specimen

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FATIGUE
TEST SPECIMENS
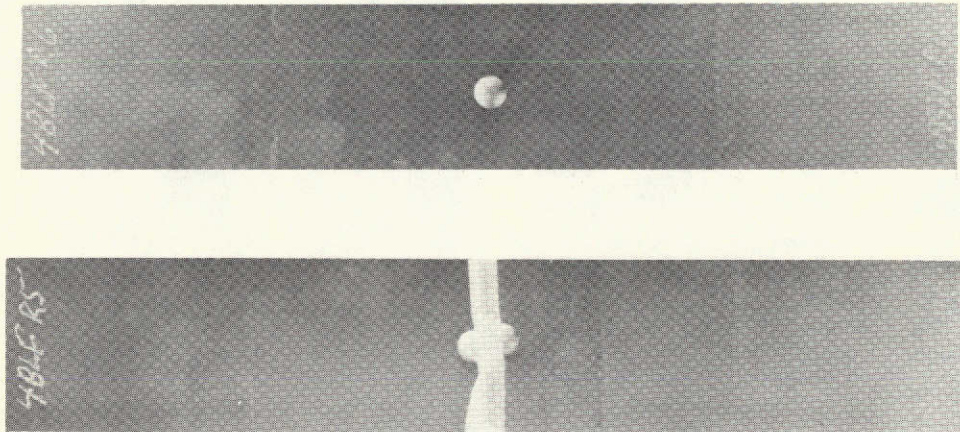
ROOM TEMPERATURE

Fig. 2.1-11 Fatigue Specimen and Typical Fracture Specimen X.67

Typical deflection and measurement curves are shown in Figures 25 and 26 of
Appendix C.   By extrapolating the modulus line to the failure load, both elastic
and plastic deflections may be read on the load-deflection curves. Typical specimens
are shown in Fig. 2.1-12.

Charpy V-Notch Testing. Impact testing was performed on sheets H-1510 and H-1535,
in both the longitudinal and transverse orientations. Testing was performed on duplicate
specimens at room temperature, $425^{\circ}K$ ($300^{\circ}F$) and $592^{\circ}K$ ($600^{\circ}F$). Typical tested
specimens are shown in Fig. 2.1-13.

Impact testing of the beryllium sheet charpy V-notch specimens was performed on a
Man Labs, Inc. impact testing machine with a 24-32.5 NM capacity. Impact test data
are graphically illustrated in Figure 27 of Appendix C. As the temperature rises,

THREE POINT BENDING
TEST SPECIMENS

ROOM TEMPERATURE

300°F

600°F

CHARPY V-NOTCH
TEST SPECIMENS

ROOM TEMPERATURE

300°F

600°F
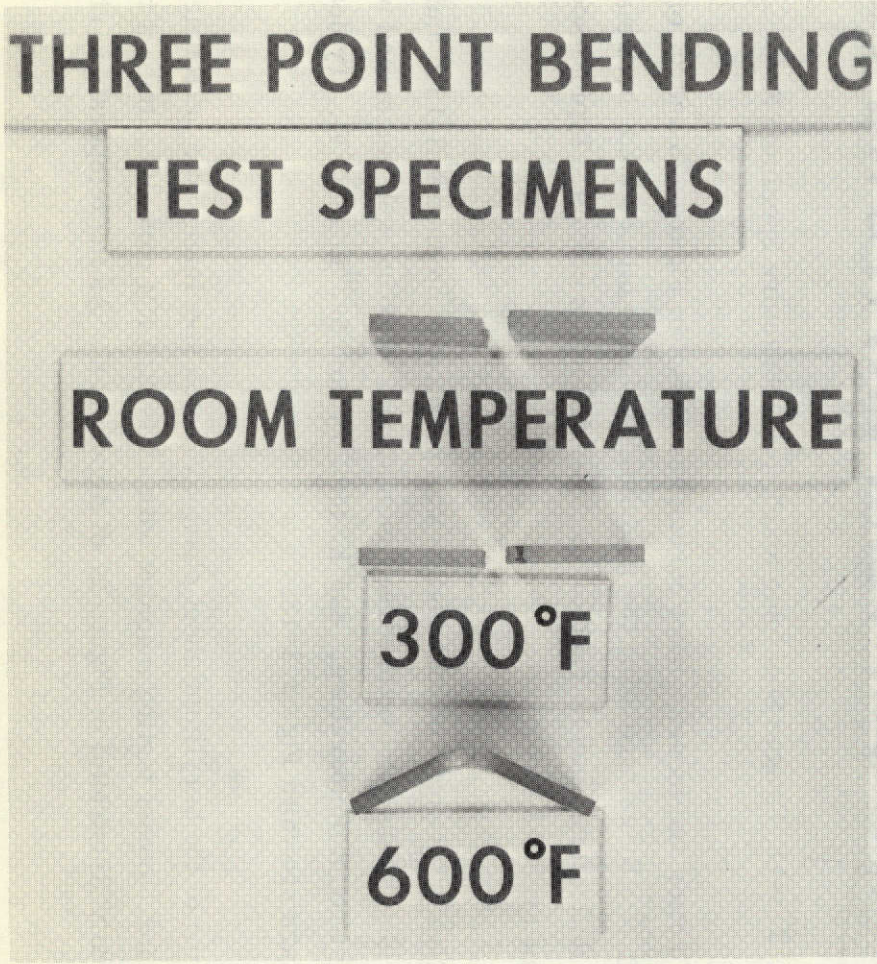
Fig. 2.1-12 Typical 3-Point Bending Specimens
After Testing
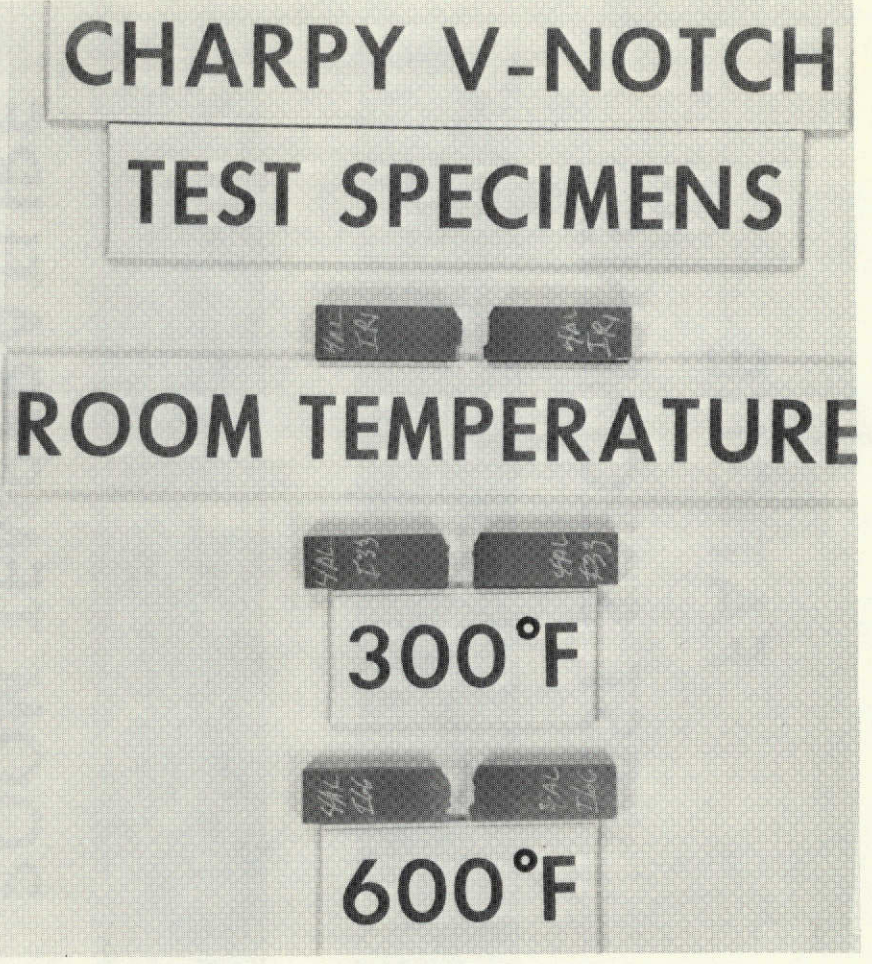
Fig. 2.1-13 Charpy V-Notch Impact Specimens,
Typical Fracture Behavior Vs
Temperature

the data trend indicates increasing toughness for the longitudinal orientation versus a relatively low increase for the transverse orientation.

2.1.4 Metallography

Figures 28, 29, and 30 in Appendix C illustrate the microstructure for a sheet from each of the three pressings. A quantitative grain size count was made as prescribed in ASTM-E112-63 using the Heyn or Intercept Procedure. Results of the count are as follows:

Sheet	Pressing	Grains/MM^3	Approx ASTM Micro Grain Size	Approx Grain* Configuration
H1514	379P	1,100,000	10.4	2.1:1 (a) 1.8:1 (b)
H1532	432P	789,900	10.1	1.6:1 (a) 1.4:1 (b)
H1516	395P	1,460,000	10.7	1.8:1 (a) 1.6:1 (b)

*Indicates average grain configuration with normal dimension of grain as referenced (ASTM E112-63 PP 7.4)

a. $nm/n\ell$

b. nm/n_t

2.1.5 Conclusion and Recommendations

Statistical analysis of both tension and compression properties reveals that modification to preexisting minimum properties for design is justified. An apparent correlation exists for behavior of mechanical properties to chemistry and grain size. The pressings used in this program possessed three different ratios for iron to aluminum. Increasing properties both at room and elevated temperature are shown as a function of the iron to aluminum ratio. Also noted is a coarser grain structure for the lower strength beryllium. Whether the grain structure is a function of chemistry or mill practice cannot be postulated at this time. This discussion should not be interpreted as discounting the influence of oxides or other minor elements in the chemistry.

Creep strengths for low levels of plastic strain appear to be adequate for design considerations of Space Shuttle-type hardware presented in this program. One must also be aware of sensitivities of techniques in measuring strain before conclusions may be made in attempts to evaluate creep strains on cyclic exposures. Scatter may be expected in creep studies, whether this is a discrete function of instrumentation or metallurgy is difficult to conjecture. In any event, observations do indicate low orders of strain within the envelope studied.

Fracture toughness has been receiving intensive investigation for most structural materials. Procedures are prescribed for preparation of fracture toughness specimens which theoretically do not degrade the structural integrity of specimens. Evaluation of fracture toughness of beryllium sheet in this program has utilized techniques considered acceptable in specimen preparation, i.e., fatigue sharpening the notch, or using root radii less than 0.0127 cm (0.005-in.) for "brittle" materials. Results of testing indicate consistent 50-percent higher K values for small root radii machined flaws. Furthermore, examination of the fatigue sharpened flawed specimens indicates very little flaw growth. Certainly, application of fracture toughness values is translated to allowable flaw sizes, and this is a function of the square of K. It appears that an investigation is justified to determine occurrence of mechanical or metallurgical damage during procedures of fatigue sharpening a flaw in beryllium. The foregoing is in contrast to the structure of preexisting or "natural" flaws in beryllium for their unique capacities to develop characteristic stress intensities and flaw-size-limitations.

Precision modulus determinations are considered accurate. The lower values reported may be viewed as representative of data observed in the scatter band for the modulus of beryllium.

Fatigue results in this program serve to confirm the known capacities of beryllium to possess high fatigue strength.

As expected for beryllium, three-point bending data indicate low bending moment values which increase with temperature. The same interpretation is also true for the charpy V-notch specimens.

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Data generated in this limited materials evaluation are considered to be quite good. The data have been used very successfully for interpretation of the structural behavior of the tested components to satisfy the intent of this program.

For future design considerations, it is recommended that a comprehensive evaluation of mechanical properties for beryllium sheet be studied for shear and bearing strengths. Lastly, not known is the influence of thermal exposures and strains during forming operation upon the residual mechanical properties at room temperature or at elevated temperature. Much work has been performed by both the suppliers and customers of beryllium to indicate that significant changes may occur as a result of thermal exposures (see Fig. 2.1-14). These relationships are strongly dependent upon the variables in mill processing by the suppliers.
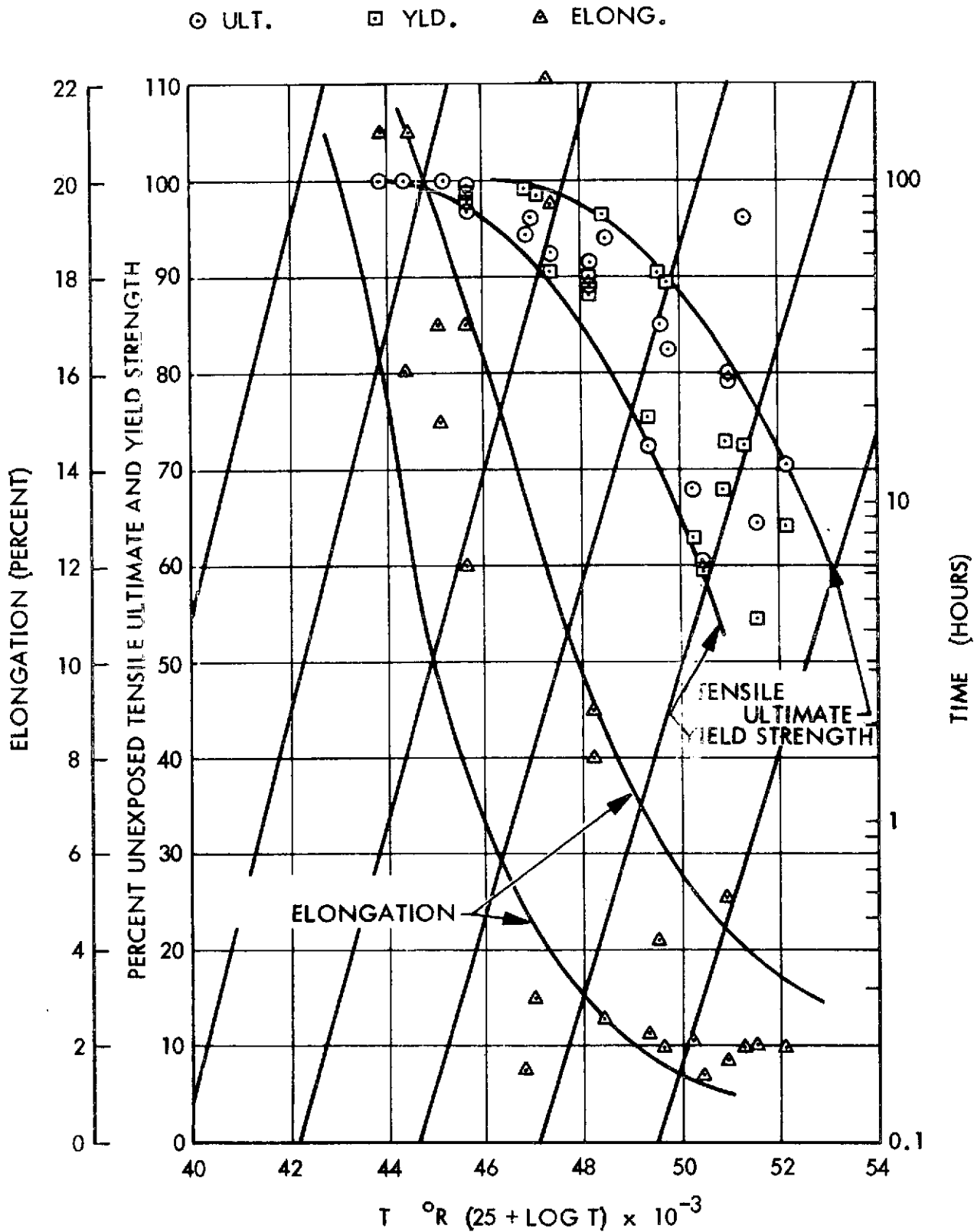
Fig. 2.1-14 Effects of Exposure Temperature and Time on Room Temperature
Tensile Properties of SR-200 Beryllium Sheet

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2.2 PHASE II – DESIGN AND ANALYSIS

Detailed structural design and analysis for the four specified structures presented in
Fig. 2.2-1 were performed in this phase of the program. Areas requiring experimental
verification were identified, and test components to provide adequate verification were
subsequently defined, designed, and analyzed. Preliminary designs developed by LMSC
indicated that test components verifying principles used in design and fabrication were
desirable. These designs were accomplished and are presented in Appendix U. Results
of the component fabrication and test were used to modify the structural designs as
required and these modifications were integrated into the two panel designs prior to
fabrication.

Structural analysis effort was performed concurrently with other tasks which provided
important information. Under Phase I, Materials Evaluation, mechanical properties
representative of the gages and sections called out in the designs were established and
subsequently confirmed by tests of the as-received material. Under Phase III, Process
Technology Development, forming limitations, joining methods, tooling requirements,
and other necessary process requirements were established for working beryllium
effectively and economically in the gages and sections required.

One of the primary problems encountered was the detail design of load introduction and
load exit systems, since eccentric loads and abrupt load transfers should be avoided.
The designs take into account final assembly requirements which involved etching all
holes after drilling to remove microcracks and surface roughness which could instigate
cracks. Because of these factors, many existing beryllium designs utilize other mate-
rials such as aluminum or titanium at splices, joints, and fittings to serve as load
introduction and load transfer members which are capable of being drilled in place on
final assembly. LMSC devoted a significant proportion of the total Phase II effort to
attachments, load distribution criteria, splices, and joints to ensure that these details
were commensurate with the structural capabilities of the basic panels.

In summary, basic structural analysis tools for design and analysis of beryllium
structures are available, although their proper application depends upon the definition

UNIFORM
LOAD
PANEL

29"

80"

7200 lbs/in ULT.

P= 350,000 lbs ULT

30-50"

72"

CONCENTRATED
LOAD PANEL

MAX. LOAD PEAK
=1.30 P/48 lbs/inch

48"

SHEAR WEB BEAM

R_1

R_2

90-100"

R_3

12" 0

12" 55 KIPS ULT

12" 110 KIPS ULT

60" 120" 120" 60"

330 KIPS ULT   453 KIPS ULT   330 KIPS ULT

340"

R_1

R_3 = 453 KIPS ULT

R_2

R_4

110-120"

TRUSS BEAM

18" 0

18" 55 KIPS ULT

18" 110 KIPS ULT.

120" 120"

330 KIPS ULT   906 KIPS ULT   330 KIPS ULT
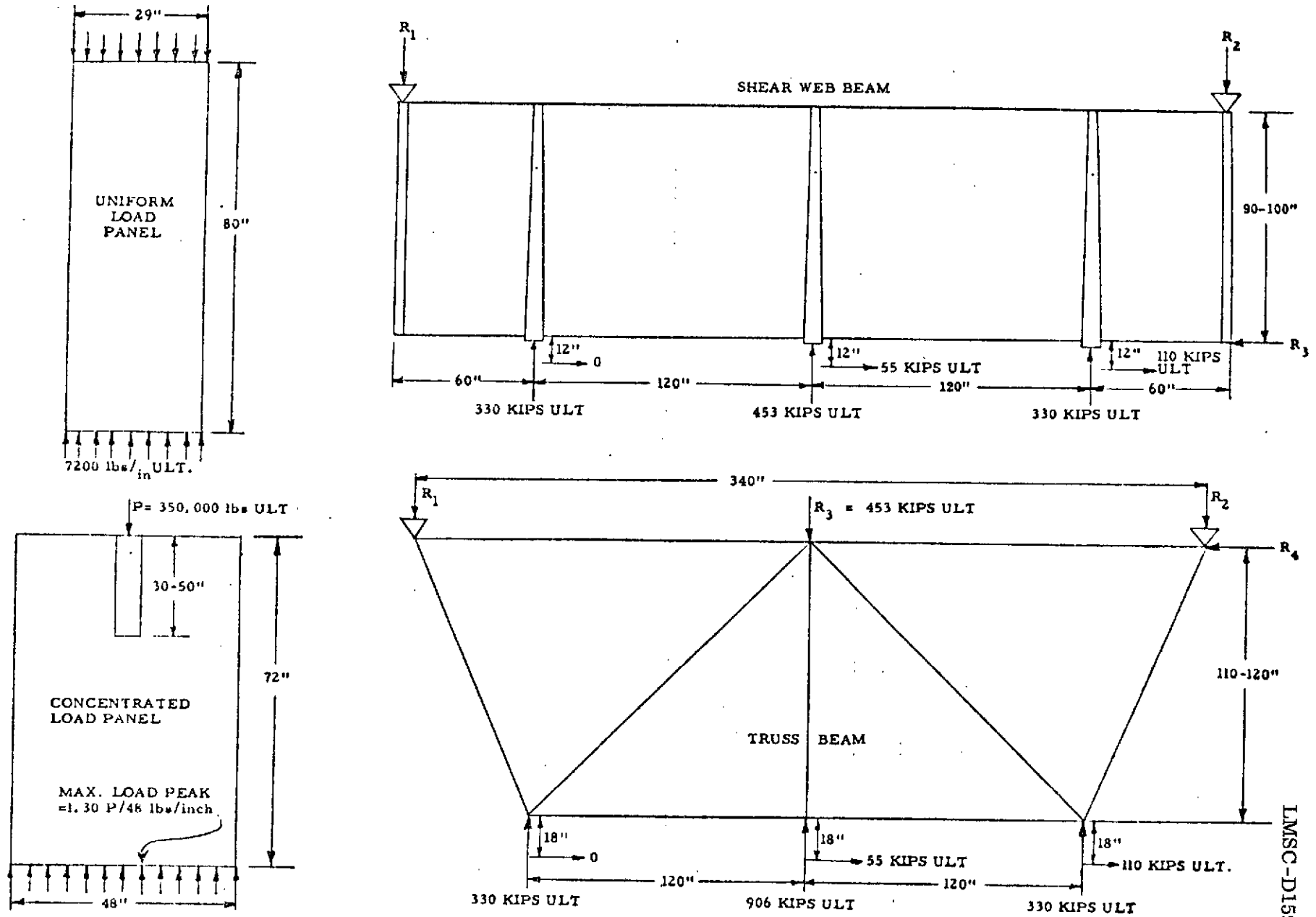
Fig. 2.2-1 Specified Designs

of material properties in the applicable gages and process technology limits.
Primary design and analysis effort was in the application of these methods and in the
design and analysis of closeouts, joints, splices, and concentrated load-introduction
fittings.

2.2.1 Design Criteria

It has been shown (Ref 6) that conventional structural analysis methodology is applicable
to beryllium structures; in particular, to those subjected to compressive or shear
loads. The primary differences observed in beryllium structures compared to struc-
tures of more conventional materials are the very small amplitude of the buckles
which form in beryllium because of the high stiffness of the basic material, and the
characteristic fracture of beryllium upon reaching the maximum post-buckling load
at room temperature. Failure modes in beryllium, reached at design temperatures
of about 260°C (500°F) or more, exhibit a more conventional, ductile-type failure
because greater elongations are available in the material in all directions. These
observations, however, have been made in the past on test specimens fabricated from
relatively thin sheet, on the order of 0.508 mm (0.020 in.) to 1.016 mm (0.040 in.)
thick. It was demonstrated experimentally in both the material evaluation and test
phases that thicker gage sheets, on the order of 2.54 mm (0.10 in.) to 3.71 mm (0.15 in.)
behave in a similar manner; in particular, it was established that mechanical properties
of the thicker sheets are at least as good as similar properties in thinner gages. A
tendency of thicker sheets to delaminate more easily and more often than thinner sheets
was not evident at all in this program.

Studies performed at LMSC have shown that beryllium, like magnesium, has a rela-
tively low proportional limit with small plastic deformations until stresses in the
neighborhood of the yield stress are reached. Consequently, a 1.1 safety factor on
yield probably did not eliminate all plastic deformation at limit load. However,
mechanical properties tests confirmed that this effect was small. Because of these
plasticity effects, LMSC developed design data curves, similar to those prepared by
LMSC in ASD TR 61-692, which included plasticity effects. Curves were prepared
for room temperature and 316°C (600°F) and supplied to NASA/MSFC as part of the

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documentation. Curves supplied include compression, shear, inter-rivet and column buckling, and also crippling, bending, and compression and shear post-buckling. Availability of these curves ensured proper consideration of plasticity effects in all designs and substantially simplified the analysis task.

The specified criteria for the program structures is summarized in Table 2.2-1, and other criteria related to material properties, attachment allowables, etc. are listed in EM B1-M2-3, Appendix F.

2.2.2 Design Considerations

In establishing the concepts for the required designs, a number of alternates were considered in relation to the configuration, the types of attachments, and the load close-outs on fittings. Careful consideration of the alternates shown in Table 1 of Appendix F led to the concepts selected, which are near optimum considering the size and scope of the program and its limited quantity of hardware. It is apparent that the availability of higher strength beryllium material would benefit the designs considerably. Higher strengths are available in extrusions, but the state-of-the-art in beryllium extrusions, particularly for conventional sections such as angles, channels, and zees, has not advanced to the point of being able to easily produce the sizes required here. This alternate was considered early in the program and rejected because of increased cost and lower allowables because of the extension process proposed. Generally, extension strengths are significantly higher than sheets in the longitudinal direction.

Design iterations were accomplished through the use of two computer programs — REXBAT and STAGS. Iterations on the closeout designs were made with the REXBAT finite element program which uses the displacement method to perform static and dynamic (eigensolution) analyses of very general structural configurations. The library of discrete elements in REXBAT includes bar elements, straight and curved beam elements, membrane and bending flat and doubly curved triangular elements, membrane quadrilateral elements, conical frustum (shell of revolution) elements, and tetrahedral and hexahedral solid elements. Orthotropic or anisotropic material properties are permitted with some of these elements. For static analyses, up to 6000 unknowns (displacement components) can be handled in a single task.

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Table 2.2-1

DESIGN CRITERIA

Parameter	Design			
	Uniform Load Compression Panel	Concentrated Load Compression Panel	Shear Beam	Truss Beam
Safety Factors				
Yield	1.1	1.1	1.1	1.1
Ultimate	1.4	1.4	1.4	1.4
Design Temperature	316°C (600°F)	316°C (600°F)	93°C (200°F)	93°C (200°F)
Edge Conditions	Simply Supported	Simply Supported		
Ring Frames	Optional	Optional		
Closeouts	Representative of production splice and provide reasonable shear and tension capability			
Material	Beryllium Panel Load Introduction Material Optional	Beryllium Panel Load Introduction Material Optional	Beryllium Fittings Material Optional	Beryllium Truss Joint Material Optional

The panels were analyzed with the STAGS two-dimensional finite-difference code to determine stability characteristics. The STAGS program, with extensions completed under contract with SAMSO and AFFDL, is based on energy minimization in combination with a finite difference discretization, a technique that for non-linear problems is far more efficient in terms of computer time than the finite element method. It is emphasized here that one of the major advantages of the STAGS computer program in stability calculations is its ability to establish the deformed state of a shell structure for each value of load and temperature; it does not merely calculate bifurcation points (buckling loads) but obtains post-buckling behavior in a rigorous manner. This quality is essential for analysis of local buckling of stiffened panels, since buckling in this case may be stable (i.e., stresses are relieved during buckling).

2.2.3 Uniform Load Panel — SKJ 201002, Rev. C

The initial proposed design at the time of the RFQ (Ref LMSC-A989431, Vol I, Fig. 1-4) for the uniform load panel incorporated all of the structural features subsequently utilized in the final design — a basic flat panel reinforced with channel section stiffeners and a doubler at each end combined with titanium close-out end fittings. The original gages were based on a 260°C (500°F) temperature environment. This temperature was later changed to 316°C (600°F) necessitating a gage increase from 0.193 to 0.229 cm (0.076 to 0.090 in.). It was then decided, in conjunction with NASA, that a conventional hardware closure would be used with end loads introduced into the plane of the skin, which was stiffened on one side only. Because bending moments were introduced, it was necessary to increase the gages again to 0.276 cm (0.110 in.) to keep the combined bending and axial stresses below 276 N/mm^2 (40 KSI). The final design, therefore, specified a minimum gage of 0.276 cm (0.110 in.) for all of the beryllium parts on this drawing SKJ 2010020 (Appendix U).

The design was initially sized as a wide column using the optimization methods presented by Emero and Spunt (Ref 7). Because of the magnitude of the ultimate compression line load, it was found that plasticity effects were significant and that the primary mode of failure was material failure in compression rather than instability buckling. This was verified later with the STAGS finite-difference computer analysis (Ref EM B1-M2-4, Appendix G). For this reason, there is little or no benefit to be gained

with the addition of ring frames to the panel, since higher stress limits cannot be tolerated. Likewise, plasticity effects preclude the use of stringer sections which are more efficient than channels.

The choice of rivets instead of screws or tension-type fasteners was based on the requirement of keeping the load distribution among the fasteners as uniform as possible. To accomplish this, fasteners which fill up the holes, mismatched or otherwise, were felt to be desirable. Thus, squeezed monel or titanium rivets whose shanks were swelled in the installation process were the prime candidates. Both types of rivets were investigated and found to be satisfactory in the process development phase. Monel was used due to cost and availability factors. The resulting design was confirmed with the test of a panel section at 316°C (600°F) at LMSC, which included the closeout design and a reasonable length of the panel (see Section 2.5).

In EM B1-M2-2C, Appendix E, it is shown that a substantial weight savings, 8.5 Kg (18.8 lb) from 37.7 Kg (83.3 lb) to 29.2 Kg (64.5 lb) can be accomplished by substituting Lockalloy fittings for the titanium end fittings and titanium rivets for the monel rivets.

2.2.4 Concentrated Load Panel – SKC 201001, Rev B

The analysis of this panel was performed with the aid of the STAGS computer code, which is described in detail on the previous page. The first design analyzed with this code showed that the load variation at the uniform load closeout fitting exceeded the allowable limits of ±30 percent. It was determined that the concentrated load fitting was too long, thereby providing a direct load path to the other end. Certain modifications, consisting of the following items, were made to alleviate this condition:

(1) The concentrated load fitting was shortened and changed from a hat section (⎍) to an inverted channel section with three legs (⊥⊥⊥).
(2) The spacing of the two stiffeners adjacent to this fitting was decreased.
(3) The fitting at the uniform load end of the panel was redesigned into a deeper, lap shear joint.
(4) The doubler on the back side of the panel was reconfigured to help spread the concentrated load.

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Successive reiterations, using prior analysis as a guide, established the final config-
uration, shown as SKC 201001, Rev B (Appendix U). A finite element analysis
(REXBAT) of the redesigned distributed load fitting was also made to determine the
stress distribution adjacent to this fitting. The results of this analysis were qualitative,
in that a uniform deflection was applied to the panel model at a certain distance from
the end fitting. Both the STAGS analyses and the REXBAT analyses showed that this
design was structurally adequate. These analyses are documented in EM B1-M2-4
(Appendix G) and EM B1-M2-5 (Appendix H).

Titanium was chosen as the end fitting material from the standpoint of cost, avail-
ability, thermal compatibility, strength, and weight. The gage and size of the fittings
were determined by the necessity for strain compatibility. Monel rivets were used
because of the "hole-filling" capability as discussed in the design of the uniform load
panel.

A component 316°C (600°F) test of the load introduction fitting and a reasonable
portion of the stiffened panel surrounding this fitting confirmed the design prior to
the manufacture of the full-size panel for test at MSFC (see Section 2.5).

A study was conducted to determine the weight savings realized if schedule and cost
constraints were alleviated. EM B1-M2-2C (Appendix E) documents this study, which
shows that a weight reduction of 23.0 Kg (50.5 lb from 163.1 lb to 112.6 lb) can be
achieved with the substitution of Lockalloy fittings for the titanium fittings and titanium
rivets for monel rivets.

2.2.5 Beryllium Truss Beam — SKR 201017

Beryllium tubes appear to be ideal members for this application, and large diameter
tubes with the required wall thicknesses have been produced which possess reported
strength properties considerably above corresponding properties in cross-rolled
sheet. For this application, a maximum outside tube diameter of six-to-eight inches
is adequate for stability, with varying wall thicknesses adjusted to carry the load in
each member. These sections could be joined by tubular weldments in titanium or
other metals which fit either inside or over the beryllium tubes and are joined to the

beryllium with bolts and/or adhesives. However, extruded beryllium tubes in this size are not readily available and the cost of these items for component tests appears to be outside the scope of the proposed program. Consequently, LMSC studied a design utilizing state-of-the-art plates and angles to form box-type sections of constant width which are joined by gusset plates at intersections. These members are some-what heavier than equivalent tubular members, principally because of the lower strength properties in cross-rolled plate. However, they may be readily made; also, gusset plates appear to be more cost-effective than tubular weldments for joining the members together. One principal drawback to the box member concept is the require-ment for etching all beryllium holes after drilling, thereby requiring disassembly of parts; however, this is not a significant problem based on present experience. Beryllium-aluminum (Lockalloy) extrusions could be utilized as an alternate in this application to provide final-assembly drilling capability.

The design of this structure is shown in Appendix U and the structural analysis is presented in EM B1-M2-8 (Appendix K). All compression members are designed as built-up box-beams of beryllium. This design, utilizing built-up members of angles and flat plates, permitted the optimization of the compression members which were subjected to beam column loading. The gusset plates at the beam junctures are designed of light-weight Lockalloy plates. The original proposal used titanium material as gusset plates; however, the Lockalloy design is lighter. The use of beryllium as gusset plates is not recommended because of the stress concentrations and discontinuities inherent in these joints and the desire for ease of final assembly drilling. These conditions require the use of materials which exhibit ductility and toughness.

The compression panel component test performed in support of the compression panel design yielded useful information on the column stability of heavy beryllium sections. Consequently, the component test in support of the thrust structure truss beam design concentrates on a representative section of a built-up truss member and the detailed splice structure, where it is joined to other members.

All fasteners (Hi-Lock) are titanium for minimum weight. A weight study of this design in EM B1-M2-2C, Appendix E, shows that it weighs 888 Kg (1954 lb).

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2.2.6 Beryllium Shear Beam — SKR 201020

The design drawing of this shear beam is shown in Appendix U and its analysis is presented in EM B1-M2-9, Appendix L. This assembly consists of beryllium shear webs stiffened with extruded beryllium angles and framed with extruded cap members. The end posts and thrust posts were designed of heat treated steel. These posts were sized by stability requirements because of column loading. Posts designed of titanium would have been of larger cross-section because of larger I (moment of inertia) requirements and hence no lighter in weight. Steel was selected in order to minimize the cross-sections, thus minimizing attachment problems. Titanium rivets were used to fasten the webs, stiffeners, and caps, and titanium Hi-Locks were used where fastener sizes exceeded 1/4 in. in diameter.

This design is based on the semi-empirical analysis of Kuhn (Ref 8) for diagonal tension field beams, with additional data taken from ASD TR61-692 (Ref 6) on the shear post-buckling strength of beryllium sheet. The two end bays were designed as shear resistant webs to preclude beam-column loading of the end posts. Likewise, the bays on either side of the central load application fitting have been made non-buckling to assist in the distribution of load from the fitting into the beam. The remaining web areas of the beam were designed for a very modest tension field beam action (K = 0.0732, where K = diagonal tension factor and varies from 0 to 1.0; 0 for shear resistant webs and 1.0 for pure diagonal tension webs). As a result, two web gages, 0.279 cm (0.110 in.) in the interior bays and 0.457 cm (0.180 in.) in the end bays, were used in the design of this shear beam. The component test results from the concentrated load panels are applicable, both for confirming the design/analysis of the load introduction fittings and for providing data on the in-plane shear-carrying capability of heavy beryllium sheet. The weight analysis conducted for this design in EM B1-M2-2C, Appendix E, shows it to weigh 1257 Kg (2773 lb).

2.2.7 Component Test Hardware

The drawings of Appendix U depict the designs for the test component hardware to be manufactured and tested at LMSC.

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Drawing SKJ 201004 shows details of the uniform load subpanel used for manufacture and test preparation. This drawing gives the detail design of the subpanel, the details of the edge restraints, and the requirements for the test instrumentation. All structural components of the subpanel are identical to those of the full-size panel; only the external overall dimensions differ. Stiffener cross-sections, gages, spacing, doublers, etc. are identical. This subpanel is not a reduced scale model. The test loading is also identical to the full-size panel and is 1260 N/mm (7200 lb/in.) of width. The structural analysis of this subpanel is presented in EM B1-M2-4 (Appendix G).

Drawing SKJ 201007 in Appendix U shows the detail design of the concentrated load subpanel, used for manufacture and testing. This drawing gives the details of the subpanel, the details of the edge restraints, and the requirements for the test instrumentation. All structural components are identical to the full-size panel parts, except for external overall dimensions. The loading is identical, 1278 N/mm (7300 lb/in. of width), at the uniform load end. The ultimate load on the concentrated load fitting is equal to the limit load on the same fitting on the full-size panel. The structural analysis of this subpanel is presented in EM B1-M2-4, Appendix G.

Figure 2.3-14 is a sketch of the truss component that was used to build and test a representative portion of the truss beam structure. This test configuration combines a brazing feasibility effort with a truss component testing effort. The size of the assembly is determined primarily by the constraints imposed by the existing brazing equipment. No attempt was made to scale down any truss member designs or loads. This structure, typical of the type of structure in the truss, demonstrates that a beryllium box-beam assembly, brazed together and mechanically fastened at its extremities, is a structurally acceptable concept.

2.2.8 Weight Trends and Results

A progressive detail weight summary was developed for all four of the basic designs to provide information on weight trends. This is summarized in EM B1-M2-2C, Appendix E, where the detailed weights are documented for the three stages of preliminary design, design release, and final assembly. These weight values, from

preliminary design to hardware, indicate that weights of optimized beryllium structures can be predicted accurately. In summary form, values normalized for comparison are:

		Uniform Load Panel		Concentrated Load Panel	
		Kg	Lb	Kg	Lb
1.	Preliminary Design Weight	22.7	50.1	44.4	97.8
	Simulated Hardware ΔW Configuration	4.2	9.3	–	–
	Minimum Gage-Analysis ΔW to As-Built Gage	2.2	4.7	3.0	6.7
	Revised Pre-Design Weight	29.1	64.1	47.4	104.5
2.	Design Changes Prior to Fabrication and Test	9.0	19.8	25.5	56.1
	Design Calculated Weight	38.1	83.9	72.9	160.6
3.	Fabricated Panel Weight	37.7	83.3	73.9	163.1
4.	Optimized Design Weight (See page 2-33)	29.3	64.5	51.2	112.6

Two inferences can be drawn from these values. One, that sufficient confidence exists in the final design that verification testing will not affect final fabricated weights (compare items 2 and 3). Results of subpanel tests have verified that the design is adequate without change. The other inference is that the weight of an actual, optimized beryllium structure can essentially be predicted in preliminary design (compare Items 1 and 4 above). Although the normalization is somewhat gross, the influence of the end closeouts, the big contributor to the design change weight (Item 2), is minimized in both the preliminary design and the optimized design. Titanium closeouts, instead of Lockalloy, were chosen early in the program to minimize cost and risk, since the central issue in the program was, of course, the overall beryllium structure. The small alterations due to stress distribution, fastener requirements, stiffener spacing, etc., were well within the accuracy of the calculations. It can be concluded that accuracy of weight prediction in preliminary design is essentially the same with beryllium as it is with conventional materials.

The two panels (uniform load and concentrated load) were designed and fabricated using titanium end fittings and monel rivets because of cost factors and schedule requirements. Investigation shows that designing with Lockalloy material (Be 38 Al) for the end fittings and titanium fasteners results in substantial weight savings.

A tabular summary of the weight savings is as follows:

Panel	Designed Weight	ΔW, Weight Savings	Optimum Weight
	Kg (lb)	Kg (lb)	Kg (lb)
Uniform Load Panel	37.7 (83.3)	8.5 (18.8)	29.2 (64.5)
Concentrated Load Panel	73.9 (163.1)	23.0 (50.5)	51.0 (112.6)

These calculations and weight savings are detailed in EM B1-M2-2C, Appendix E. An additional study was conducted of the uniform load panel design in which various candidate materials were compared. Using a Z-stiffened wide-column computer program, results were obtained and are summarized in Table 2.2-2 (refer to EM B1-M2-10, Appendix M for details).

Table 2.2-2

CANDIDATE MATERIALS SUMMARY

Panel Material	Temperature		Unit Weight	
	^{o}C	(^{o}F)	Kg/m^2	(lb/ft^2)
Beryllium Cross-Rolled Sheet	316	(600)	8.78	(1.797)
Boron Aluminum	316	(600)	9.51	(1.943)
Aluminum 2024-T81	149	(300)	17.70	(3.621)
Aluminum* 7075-T6	149	(300)	17.86	(3.657)
Titanium 6A14V	316	(600)	23.90	(4.896)
Steel AM350	316	(600)	31.22	(6.394)

*In addition, aluminum would require weight for thermal insulation to reduce temperature to 149°C (300°F).

Based on the specified panel design conditions, the least weight candidate material for the uniform load panel was beryllium. Relative to beryllium, unit panel weights for boron aluminum, aluminum, titanium, and steel indicate weight penalties of 8 percent, 100 percent, 170 percent, and 260 percent, respectively. The use of unidirectional properties for the boron/aluminum in this study is felt to be optimistic.

The shear and truss beam were also parametrically sized using the SNAP/FSD finite element code which automatically generates fully stressed designs of large bar and shear panel structures (see EM B1-M2-12, Appendix V). Candidate materials included beryllium, boron aluminum, 7075 aluminum, 2024-T81 aluminum, 64 -4V titanium, and AM-350 steel. A weight comparison of candidate shear and truss beam materials is summarized in Tables 2 and 3 of Appendix, respectively. Considering one material only, beryllium yields the lightest structure in both cases; however, for both shear and truss beams, the least weight candidate was a combination of boron aluminum for axial elements and beryllium for shear panels. Because of low shear strength, boron aluminum is the heaviest candidate material for the shear beam. Because of high elastic modules and relatively low allowable stresses, beryllium produces the least thrust structure component deflections.

2.2.9 Cost Analysis

Costs of complex beryllium spacecraft structure are a matter of conjecture because of the lack of applicable historical data. The data sample developed in EM B1-M2-11, Appendix N, will also apply to only a small segment of the whole population of beryllium structures. Even for the structures examined, Lockheed's background and experience in beryllium work may affect the cost significantly. The primary thrust of the referenced document, then, is to determine (1) the cost of the deliverable panels as produced and a typical cost per pound as related to aluminum; (2) a manufacturing complexity factor as related to aluminum; and (3) a predicted cost of the truss and shear beams based on both ROM detail estimates and the previously-mentioned factors for comparison. Results show that cost values are somewhat less

than expected for program structure, if standard complexity factors are used, and that there is a reasonable agreement (considering typical cost relationships) between values derived from estimates and those derived from panel based factors. Rates of production similar to Space Shuttle needs are shown to have little effect on costs. Appendix N elaborates on these points and provides the background, details, and qualifications involved in the cost analysis.

In summary form, numerical results are:

- Average cost per pound-panel derived = 307 $/lb
- Typical cost per pound-alum aircraft structure = 120 $/lb
- Derived complexity factor compared to alum (307/120) = 2.56
- Documented complexity factor = 2.9
- Truss Beam
    - Estimated total cost − ($/lb = 227) = $443,428*
    - Factored total cost − ($/lb = 329) = $643,000
- Shear Beam
    - Estimated total cost − ($/lb = 281) = $778,036
    - Factored total cost − ($/lb = 256) = $710,000
- Percent decrease in cost due to increase in production (recurring costs only) = 10%

*Low forming and tooling costs are anticipated with the truss as designed.

Weight/cost sensitivity factors for Space Shuttle demonstrate that the employment of beryllium is indeed cost effective. In fact, using the results of a panel trade study (EM B1-M2-10, Appendix M), indicating weight differentials between beryllium and aluminum and the associated cost factors, there would be very little difference in cost, since the aluminum structure is twice as heavy as the one using beryllium and requires insulation to restrict the temperature to 149°C (300°F).

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2.2.10 Conclusions and Recommendations

It has been demonstrated in this program that the basic tools of structural design and analysis were adequate to meet the specified requirements and objectives. Conventional methods of analyses are utilized successfully in predicting stress levels and strain distributions. Where high local stresses were encountered, it was determined that stress redistribution would occur without precipitating catastrophic failure; indeed, this ductile property of the material was demonstrated in the testing of the two test panels, thus imparting greater confidence to designs in the plastic range. Multiple holes and rivets that were of prime concern did not cause any problems in the gages used. Two precautions incorporated in the designs to preclude problems in this area were (1) maintain a minimum edge distance (e/d) of 2, and (2) maintain a minimum of four hole diameters distance in rivet spacing. Discontinuities caused by abrupt change of sections were minimized throughout the designs. All designs were made compatible with the requirements for chem-etching after machining or drilling and prior to assembly.

The results of both weight and cost analyses were encouraging for the types of program structure examined. Weights were shown to be predictable and costs lower than predicted by presently documented factors.

The experience gained in this project in the use of beryllium in large structural components indicates that, with certain minor precautions, this material can be worked in a manner similar to other conventional materials. It is recommended that strong consideration be given to beryllium as a reliable structural aerospace material. It is also recommended that investigations be continued in hole tolerances, fasteners, and compatible combinations of braze plus fasteners — all contributing to the extension of present knowledge into more complex designs.

2.3 PHASE III, PROCESS TECHNOLOGY DEVELOPMENT

This phase of the program is designed to evaluate, select, and refine where necessary those available fabrication processes that may be required for beryllium structures applicable to Space Shuttle design requirements, especially those selected for this program. The primary objective is to determine and ensure the availability of manufacturing technology for beryllium structures applicable to the orbiter. Development work was constrained within the requirements stated and conducted in harmony with Phase II, Design and Analysis as well as phase IV, Fabrication.

The criteria governing preliminary process selection were (1) feasibility, (2) reproducibility, and (3) cost, in that order. The order was considered more effective during the initial iteration of design concepts to provide maximum freedom. Once the feasibility of a design was established, cost became the prime criterion for further screening of processes to be selected.

Critical factors of a process such as tooling, equipment, skill, control (inspection), etc., were evaluated taking the complete structure and the fabrication cycle into consideration. The degree to which each of these factors was evaluated, both by itself and its interrelations to others, was based on the conditions of the development program on hand. Therefore, the final modes applied were not necessarily suited for production conditions. For example, dimensional conformance was accomplished by discrete measurements in lieu of limiting gages that might be more effective for production.

A plan (EM B1-M3-1, Appendix O) that discusses all the processes required for this program and identifies specific process areas to be refined, was prepared at the beginning of this contract. This plan was one of the contractual items, and its approval established the scope of process development efforts to be completed.

In brief, the plan identifies the following list of major processes as being required by this program as well as the manufacture of other typical beryllium structures for the Space Shuttle:

- Mechanical cutting, routing, and deburring
- Mechanical drilling

- Electrical (spark) machining — EDM
- Chemical etching (with or without electrical energy)
- Surface cleaning and preparation (mechanical or chemical)
- Thermal forming
- Mechanical joining (fasteners)
- Fluxless brazing (metallurgical joining)

Excluded from the above list are some processes not required for this program but which could also be applicable under special conditions to other beryllium designs. Processes such as adhesive bonding, resistance spot-brazing, etc., have been used successfully. Since they are unique in their applications and could only be considered as alternates to processes selected, these processes were therefore excluded from this program. Furthermore, the selected processes listed above are sufficiently encompassing to cope with virtually any type of built-up structural assembly.

Of those processes considered applicable for this program, LMSC has established in-house on-going capability in each of these areas. As one of the largest users of beryllium in its many forms, LMSC has acquired and maintained a versatile capability in terms of facilities, techniques, and skills for the fabrication of small to medium size beryllium structures. For structures larger than those produced at LMSC, such as the full-scale compression panels designated for this contract, some areas of the existing process capabilities need to be extended, especially where the parameters of a process may not be simply scaled up to cope with increase in size. Actual trial fabrication must be conducted to determine the degree to which the size of a component can affect process control. One such area is in the hot forming of long slender channels as compared to the forming of a medium size panel having a rectangular proportion. Of the many processes required for the fabrication of the structural assembly considered in this contract, there were only three areas where some development work was considered necessary to evaluate the effect of size on the process parameter. As discussed in the Process Development Evaluation Plan (Appendix O), these areas are:

    1. Straightness and flatness control on thermal forming of long slender channels, about 7.62 x 203.2 cm (3 x 80 in.)

2. Fit tolerance limits for large fastener clusters

3. Assembly of tubular members by fluxless brazing

This report documents and summarizes the highlights of the work conducted and the results obtained during the process development phase, specifically in the three areas mentioned above. Because of this early investigative work, which identified those critical process parameters involved with large structures, appropriate adjustments on certain processes were made. As the result, fabrication of the full-size compression panels was accomplished without any significant problem.

2.3.1 Thermal Forming

Cross-rolled beryllium sheet can be formed, to a degree, at room temperature, although under a very selective condition. Reliable forming must be accomplished at elevated temperatures. The geometrical accuracy and internal stress level of a formed part depend greatly on the dimensional stability of the forming die over the entire temperature range, the temperature distribution over the part, and the part forming cooling rate. Therefore, successful forming operations require that the forming die design must provide a positive means to adequately control the thermal energy flow to and from the die over the entire forming cycle. The degree to which the energy flow is to be controlled depends upon the specific configuration of the part being formed.

The first step of the development work was to establish and prove the forming die design. With the concurrence of the design leader, a common inside dimension of 7.62 cm (3.00 in.) was selected for both the 0.315 cm (0.124 in.) and 0.355 cm (0.140 in.) thick channels. This allows for a common male forming block. Stainless steel male and female forming blocks were fabricated from standard size 5.08 x 7.62 cm (2 x 3 in.) bars and each mounted on a full-length base plate, which also served as the mounting plate. Heat energy was provided by two massive ceramic bolster platens having cast-in electrical heating elements. Each of the upper and lower bolster platens have three independent heating zones running the full length 243.8 cm (96-in.) of the platen to facilitate temperature control. A complete "fence" of insulating

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material was placed around the form blocks, both at closed and open positions, to control heat loss. Local adjustment of the amount of insulating material provides a means to balance form block temperatures.

For the limited quantity of parts involved in this contract, this design (though not suitable for production conditions), is considered to be most cost effective for the requirements on hand (Fig. 2.3-1). Since our plan calls for using the most experienced hot-forming operators to man all the forming operations for this contract, extensive use of automatic temperature control circuits was deemed unnecessary. Our experience has shown that beryllium displays a range of color from 985° K (1300° F) to 1038° K (1390° F), which registers its temperatures quite accurately. An experienced operator can consistently "read" beryllium temperatures within this range by the exact shade of its color. Since it is always difficult and cumbersome to attach thermocouple junctions to a form blank, LMSC has regularly used the visual method for determination of forming temperature for beryllium. During the preliminary temperature calibrations of the forming die, small pieces of beryllium were placed at intervals along the length of the lower (male) forming block to serve as temperature indicators. By adjusting the electrical power to the various sets of heating elements in the ceramic bolster platens and manipulating the mass of the insulating "fence" locally, the desired temperature balance over the working area of the forming blocks was quickly obtained. Finally, the exact temperature distribution of a full-length trial blank was verified with the use of thermocouples attached to the blank. This arrangement was then retained until all the required channels were formed. Although the upper ceramic bolster platen cracked under usage and the heat source was replaced by high temperature "cal-rods," the basic method of obtaining temperature balance remained the same.

Once a blank is formed, the work must be cooled rapidly, but uniformly, to at least below 592° K (600° F) if distortion and excessive residual stress are to be minimized. For very thin-gage parts having a relatively large surface area, active control may be necessary to maintain a temperature balance during cool down. For parts having suitable surface area-to-weight ratio, passive control often is adequate to achieve the desired temperature balance. This is usually economically accomplished with a
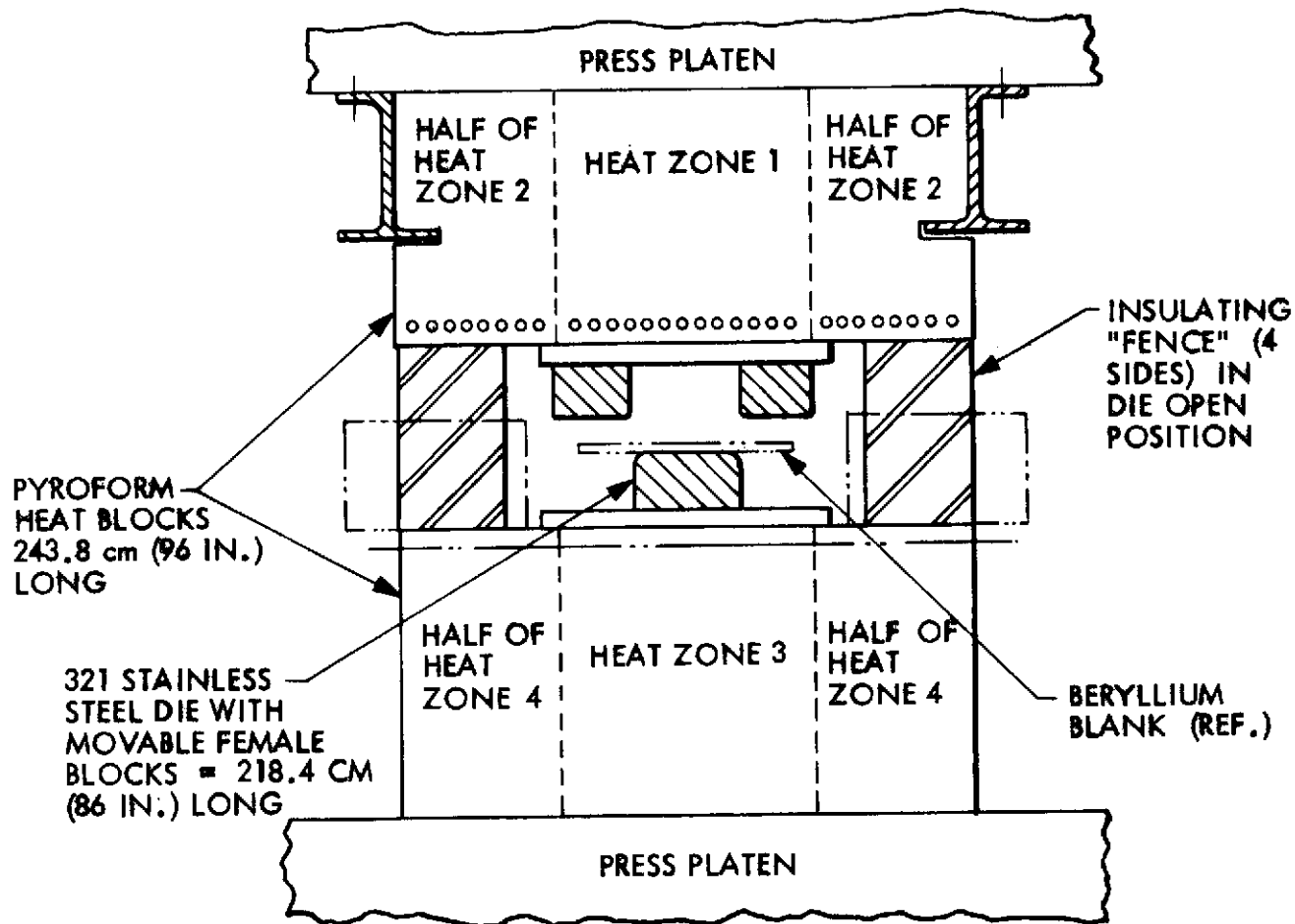
2-40

Fig. 2.3-1 Hot Form Die Schematic

close-end insulated cooling chamber into which the formed article, near its forming temperature, is sealed in and allowed to be cooled gradually. The rate of heat dissipation through the wall of such a chamber is usually low enought as to not cause significant temperature difference over the length of the formed part.

Since the ratios of length-to-width of the stiffener channels are very large, and the time required to remove and transfer a formed 203.2 cm (80 in.) long channel from the forming die to a cooling chamber is considerably longer than smaller parts, it was not certain whether the passive cooling technique would be satisfactory. As stated earlier, this was the most economical method, and since the risk in value was moderate, it was decided to try this passive control method.

An ordinary 15.2 cm (6 in.) diameter light-gage steel pipe was used as the body of the cooling chamber. Over the outer periphery of the pipe, several layers of insulation were spirally wrapped. High temperature insulation wool was placed along the full length of the interior to prevent direct contact between the hot channel and cold wall of the pipe. One end was closed with insulation and the open end was provided with an insulating plug (Fig. 2.3-2). This entire cooling chamber was suspended from overhead and aligned closely with the forming die. As quickly as a formed channel could be stripped from the male forming block, it was rapidly transferred into the cooling chamber until temperature of the channel was less than $538^{\circ}K$ ($500^{\circ}F$), so that it could be removed from the chamber and placed on an insulated bench top to continue cooling. The first two full-size channels tried showed no measurable deviation from the dimension of the forming die and were well within the required straightness and flatness tolerances. This indirectly signified that the temperature distribution over the length of the channel was well within the permissible range to avoid significant distortion and residual stress. Actual temperature readings of the channel during the cool-down cycle were decided to be unwarranted because of the expense involved. As can be seen from Figs. 2.3-1 and 2.3-2, any thermocouple wires attached to the form blank will interfere during its entry into the cooling chamber. The wires must be doubled up to come out of one end. Such excessive handling of the wires could jeopardize the reliability of any temperature readings obtained. The other alternate method was to run the thermocouple wires through the wall of the cooling

Fig. 2.3-2 Cooling Tube With Insulating Plug

chamber and measure only the air temperatures at various interior zones along the length of the cooling chamber. It would be very difficult and inaccurate to extrapolate the actual temperature of the channel from air temperatures. Any readings thus obtained could only be used for reference and contribute little value. The primary purpose of obtaining actual temperature readings on the channel was to provide a point of reference for redistribution and equalizing the temperature distribution during the cool-down cycle should excessive distortion be displayed in a formed channel upon cool-down to room temperature. Any waviness, twist, bow, etc., (especially in the flange) of more than 0.0125 cm (0.005 in.) deviation from a straight line would make it difficult to fasten the channel to the panel with rivets.

The result of the first two trial channels indicated that no further adjustment on temperature distribution was necessary. The cooling chamber, as constructed, was satisfactory and was used to form all channels required for this contract. One added feature worth noting was that it took about 20 minutes to cool one channel past the critical temperature of 538°K (500°F). This time was slightly shorter than that required to bring the temperature of a form blank up to forming temperature in the die. It was possible to maintain maximum utilization of the die without delay.

The basic operational cycle as described above prevailed except for one or two minor modifications. In line with the basic objective of this contract, which is to economically establish the feasibility and availability of technology for the design and manufacture of large cross-rolled beryllium structures to be cost-effective, costly permanent type of tooling necessary for production conditions was excluded throughout. The use of ceramic bolster platen is an example. Such tooling is only good for a limited number of operating cycles and often requires extensive repair to withstand a score of operating cycles. However, our experience has shown that for development work where experienced and skilled operators perform the work, this is the most cost effective approach.

Upon completion of all the thin gauge 0.315 cm (0.124 in.) channels, the forming die was modified for the heavier gage. As expected, the increased forming load on the ceramic platen soon caused the upper block to develop excessive cracks and rendered it unusable. To correct this situation, the stainless steel female forming block

assembly was modified to receive about six sheathed tubular heater strips running the full length of the die between the two female form blocks. This new heat source replaced that provided by the upper ceramic platen. A large cross-section steel I-beam replaced the plywood spacer previously used as a compression member.

Thermal forming operation was resumed without any significant incident. Near the end, a slight spreading of the female die, caused by elevated temperature creep of the anchoring studs, caused incomplete closing of the channel flanges. Extensive rework of the forming die would have been required to restore it to its original condition. Because there were only a few channels involved, the cost for reworking the die was not warranted. Under careful control, and using the male forming block as a core, these channels were hot-sized, using the basic forming die as the working surfaces. The dimensional deviation was corrected without delay. All the channels formed were well within the allowable straightness and flatness tolerances. Figure 2.3-3 illustrates this quality. Other than those few channels mentioned above, which required hot sizing, all channels were acceptable in the as-formed condition. Final trimming and cutting were accomplished by both EDM and end-milling methods.

Evaluation of the thermal forming development is presented in Table 2.3-1.

Table 2.3-1

THERMAL FORMING DEVELOPMENT

	Exceed Require- ment	Adequate For Program	Improve- ment Needed
Design of Development Task		X	
Meeting Objective	X		
Die Design		X[1]	
Equipment Set-up		X	
Forming Method		X	
Test Method		X	
Application for Current Design	X		
Application for Future Reqm'ts		X[2]	X

Table 2.3-1 (Contd)

Comments:

Objectives were accomplished economically, and effectively exceeded expectations.

Notes:

(1) More rugged anchoring of the forming blocks might improve the performance. Ceramic bolster platen could be replaced by sheathed heater strips.

(2) A better method to transfer very thin gage and long stringers from forming die to cooling chamber may be needed. Also, hot-sizing may become necessary for some configurations.

2.3.2 Fastener Development

Although the mechanics of installing a squeezed rivet is well known, hardly any information or data are available on the effect of either the degree of upset on a high-strength rivet or the fit-tolerance on the performance of a fastener cluster installed into cross-rolled beryllium sheets. The objective of this development task is to determine the magnitude of rivet squeeze and the mismatch or hole oversize that can be allowed.

In a multiple-fastener joint, made up of isotropic materials such as aluminum or steel, an applied force to one side of the joint is proportionately distributed through the individual fasteners to the other side according to the location of the centroid of the fasteners. Each fastener is assumed to be fully effective regardless of the fit-tolerances because of the ability of the material to redistribute applied stresses. Even when some fasteners within the cluster may be the only ones to resist the applied force initially (tighter fits), slight yielding on the bearing areas of these holes will immediately bring all the other bolts into action and cause redistribution of the applied force in accordance to the centroid principle. With a fastener cluster in cross-rolled beryllium sheets, this may not be so. Cross-rolled beryllium sheets, being anisotropic, can not be expected to redistribute the applied stresses at the same level as aluminum or steel. Generally, one must design and fabricate beryllium assemblies with meticulous care, using every precaution to ensure match fit of all holes.
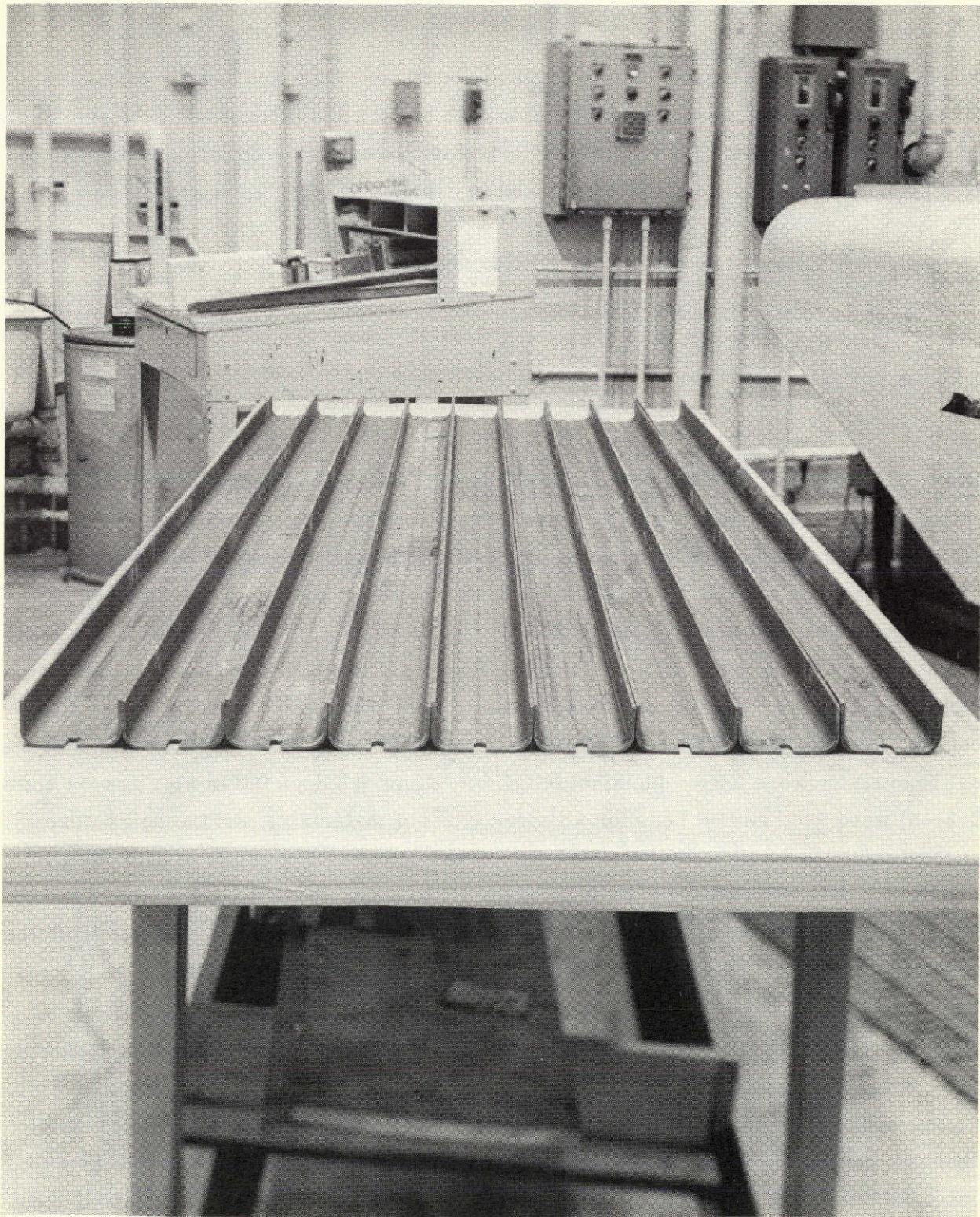
Fig. 2.3-3 Hot-Formed Channel Section Stiffeners for Uniform Load Panel

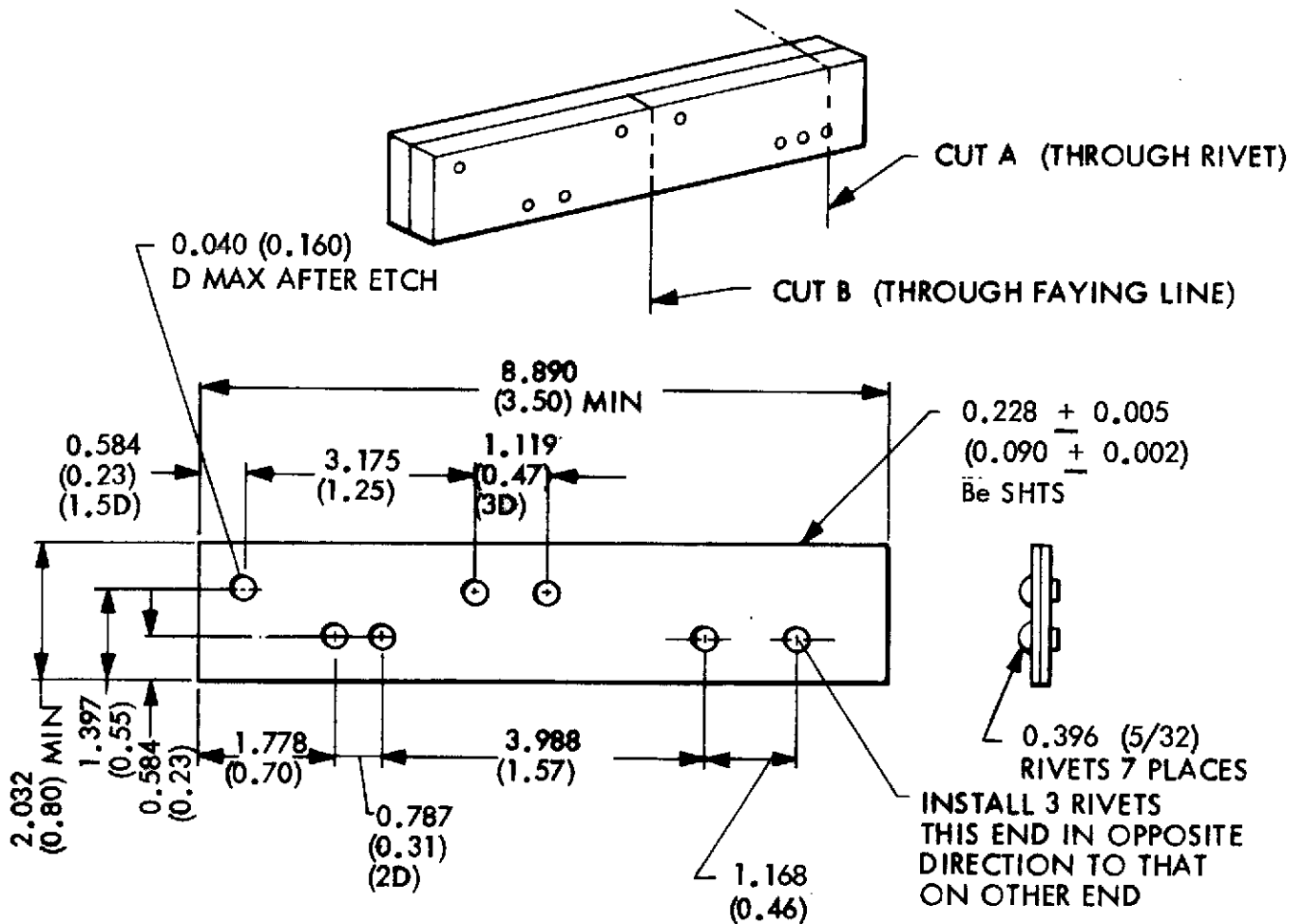**LOCKHEED MISSILES & SPACE COMPANY**

Where rivets are to be used, softer squeeze aluminum rivets are usually used. This approach has generally kept the fabrication cost high, while discouraging the application of beryllium structure. It is therefore desirable to establish a better understanding in this area so that a more realistic approach to design and fabrication may be possible.

Process development tasks were designed to determine

- Hole filling characteristics of high-strength squeezed rivets, namely, monel, c.p. titanium and Beta-III titanium
- Effect of fit variance of individual fasteners on the load distribution mode of fastener cluster

Hole Filling Characteristic of Squeezed Rivets. Three high-strength materials were considered for the rivets, namely, monel, c.p. titanium, and Beta-III titanium. A series of experiments were conducted to determine the behavior of rivets made of these materials when they are installed into cross-rolled beryllium sheets by squeezing. Monel costs less and is equal in strength to c.p. titanium, which is lighter. Beta-III is the strongest and most costly. Titanium rivets are about 6 to 8 times as costly as monel rivets. All three types were included in the study to gain data for future application. To reduce the number of variables, only 0.476 cm (3/16 in.) diameter universal head rivets were used. Identical beryllium strips (as depicted in Fig. 2.3-4a and 2.3-4b) were used as test beds for all three types of materials. All the holes were accurately drilled with a drill template in a fixed pattern. The holes in each strip of a matching pair were enlarged by 0.00762 to 0.01016 cm (0.003 to 0.004 in.) in diameter. Half the number of rivets installed in each test specimen were inserted from the opposite direction. This was designed to identify any orientation effects.

Prior to riveting the test specimens, trial runs were made to determine the minimum squeezing forces required for each material using a slow action hydraulic plunger. The rivets were installed in beryllium plate approximating the test specimens' conditions. It required about 13344 - 15568 N (3000 - 3500 lb) axial force to adequately upset both the monel and c.p. titanium rivets, while the Beta-III rivets required about 17792 - 20016 N (4000 - 4500 lb). For the test specimens, monel and c.p. titanium rivets were squeezed with a 15568 N (3500 lb) constant force, while the Beta-III rivets were squeezed with 20016 N (4500 lb) constant force.

CUT A (THROUGH RIVET)

CUT B (THROUGH FAYING LINE)

0.040 (0.160)
D MAX AFTER ETCH

8.890
(3.50) MIN

0.584
(0.23)
(1.5D)

3.175
(1.25)

1.119
(0.47)
(3D)

0.228 ± 0.005
(0.090 ± 0.002)
Be SHTS

2.032
(0.80) MIN

1.397
(0.55)

0.584
(0.23)

1.778
(0.70)

3.988
(1.57)

0.787
(0.31)
(2D)

1.168
(0.46)

0.396 (5/32)
RIVETS 7 PLACES

INSTALL 3 RIVETS
THIS END IN OPPOSITE
DIRECTION TO THAT
ON OTHER END

GENERAL NOTES SAME AS TYPE A SPECIMENS EXCEPT DIMENSIONS AS NOTED — CM (IN.)

SPECIMEN B_1 — ASSEMBLE WITH SQUEEZED MONEL RIVETS

SPECIMEN B_2 — ASSEMBLE WITH SQUEEZED C.P. OR BETA III RIVETS

SPECIMEN B_3 — ASSEMBLE WITH EXPANDABLE BLIND Ti FASTENER (HUCK MLS OR EQUIV)

Fig. 2.3-4a A-Type Beryllium Specimen

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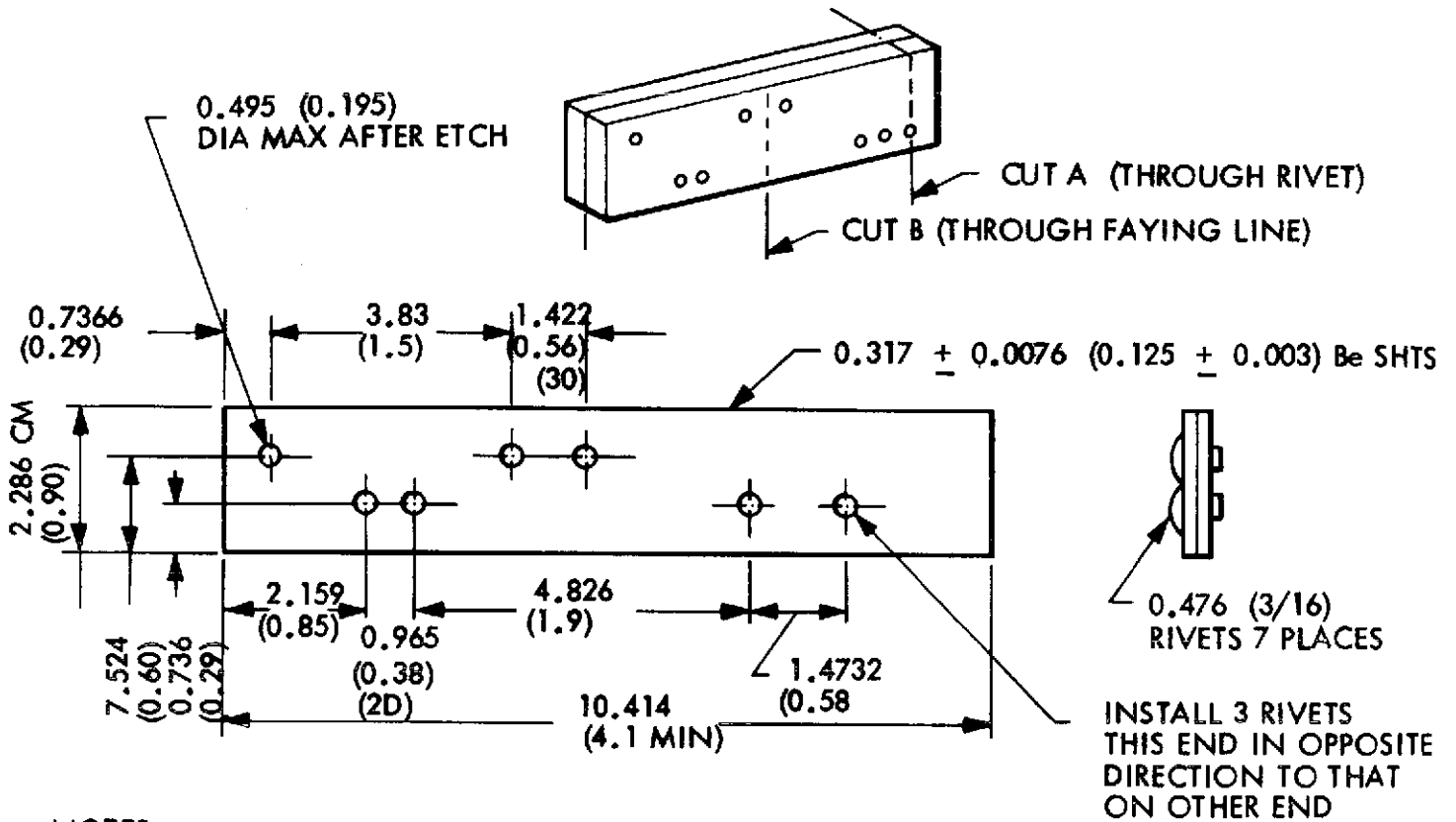
NOTES:

1. DIMENSIONS ARE CM (IN.)

2. ETCH HOLES IN ONE SHEET PER ASSEMBLY 0.005-0.007 CM (0.002-0.003 IN.) LARGER. INSERT RIVETS FROM SMALLER HOLE ON ONE END, OPPOSITE ON THE OTHER.

3. SPECIMENS MAY BE CUT FROM A LARGER ASSEMBLY.

4. IF EDM IS USED TO DRILL HOLES, SO IDENTIFY.

5. IDENTIFY MATERIAL HISTORY IF AVAILABLE.

SPECIMEN A_1 — ASSEMBLE WITH SQUEEZED MONEL RIVETS.

SPECIMEN A_2 — ASSEMBLE WITH SQUEEZED Ti RIVETS (C.P. OR BETA III)

SPECIMEN A_3 — ASSEMBLE WITH EXPANDABLE Ti BLIND FASTENERS (MLS OR EQUIVALENT)

Fig. 2.3-4b B-Type Beryllium Specimen

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All test specimens were subsequently dissected, as indicated in Fig. 2.3-4, and examined under a 10X magnification. All rivets expanded in the hole and virtually filled any void within the hole regardless of the orientation of the rivet (Figs. 2.3-5 and 2.3-6). However, monel rivets appeared to flow more readily when squeezed, and packed the hole more uniformly.

The results indicates that 0.476 cm (3/16 in.) diameter rivets made of these three types of material will fill up at least a 0.0102 cm (0.004 in.) oversize hole when installed in 0.635 cm (1/4 in.) thick material by a constant squeezing force. If weight is not critical, monel rivets are the most economical. The prime objective, to determine whether these rivets would expand fully within a hole when they are upset by squeezing, was established and no further attempt was made to quantify the result.

Based on these tests, the guidelines established for both design and manufacturing were that Universal head monel rivets will be installed with a constant squeezing force suitable for each diameter, regardless of length.

An air piston with regulator was adapted for installation of all rivets. At a preset pressure of the air supply (by regulator) to the piston, each rivet of the same diameter was upset by the same squeezing force. The equipment used is shown in Fig. 2.3-7.

Fastener Fit-Tolerance on Load Distribution of a Cluster. The candidate structural assemblies for this contract involve the use of many rivets in close clusters. Although extreme care will be exercised in fabrication of these parts, 100 percent match-fit of all holes cannot be expected. It was, therefore, very desirable to determine to what extent individual fastener fit-tolerances could affect the ability of a fastener cluster to transfer loads.

A series of specimens, as depicted in Fig. 2.3-8, were fabricated and tested to destruction. By enlarging one of the six holes in the pattern at various positions and testing them under an identical loading condition, the results would indicate whether redistribution occurred. Table 2.3-2 summarizes the test results and Figs. 2.3-9 through 2.3-13 show the load strain curves of all specimens (15) listed. A very slow
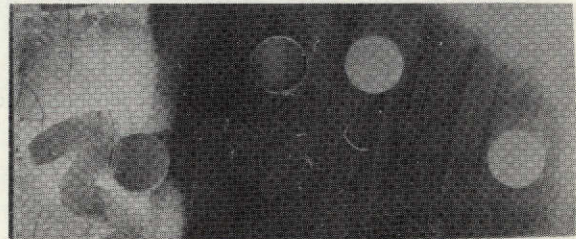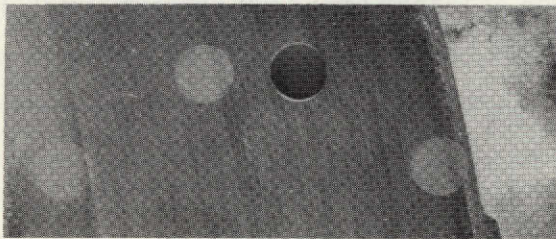
2-51
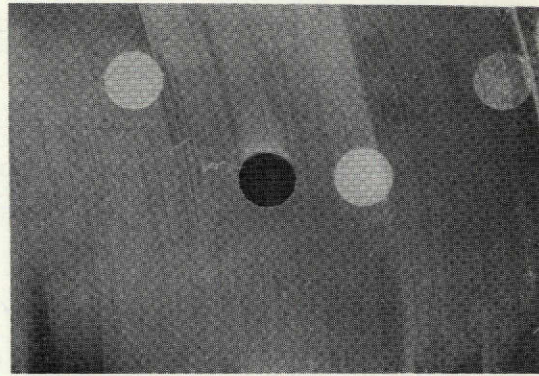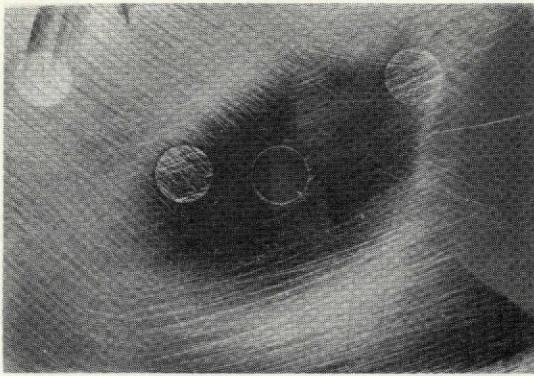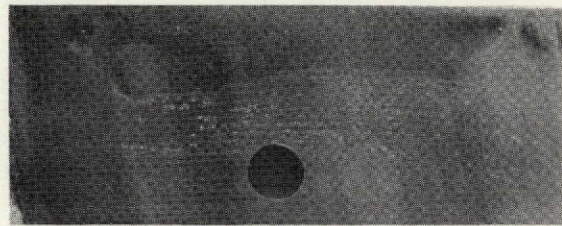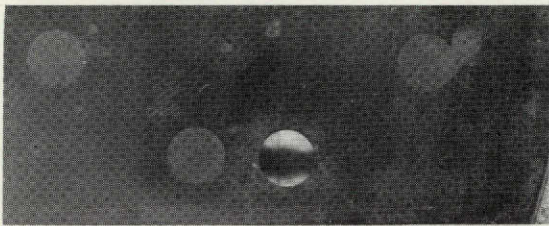
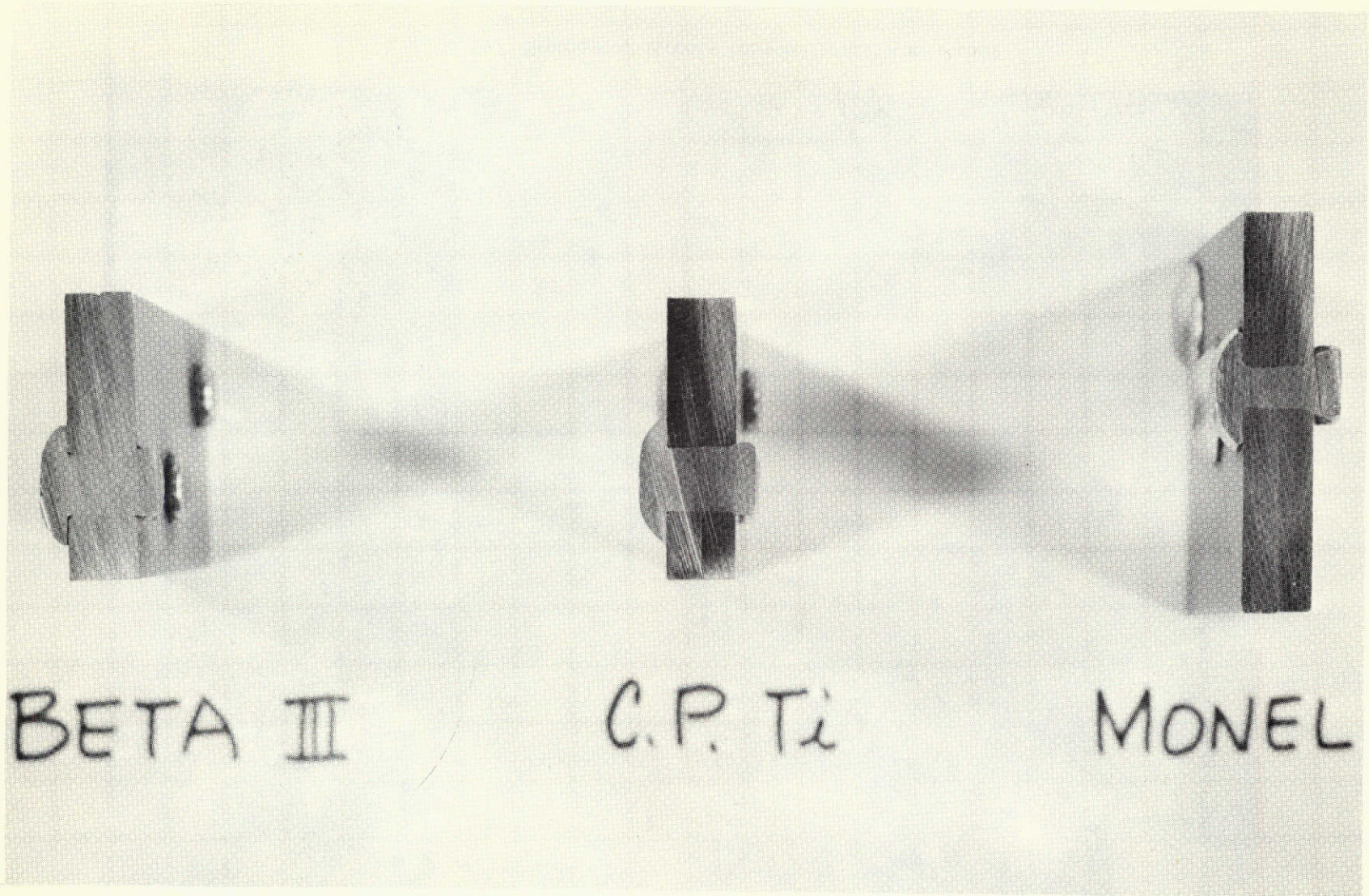Fig. 2.3-5 Plan View of Dissected Rivet Specimen (Note Filled Holes)

Fig. 2.3-6 End View of Dissected Rivet Specimen (Note Filled Holes Through Full Depth)

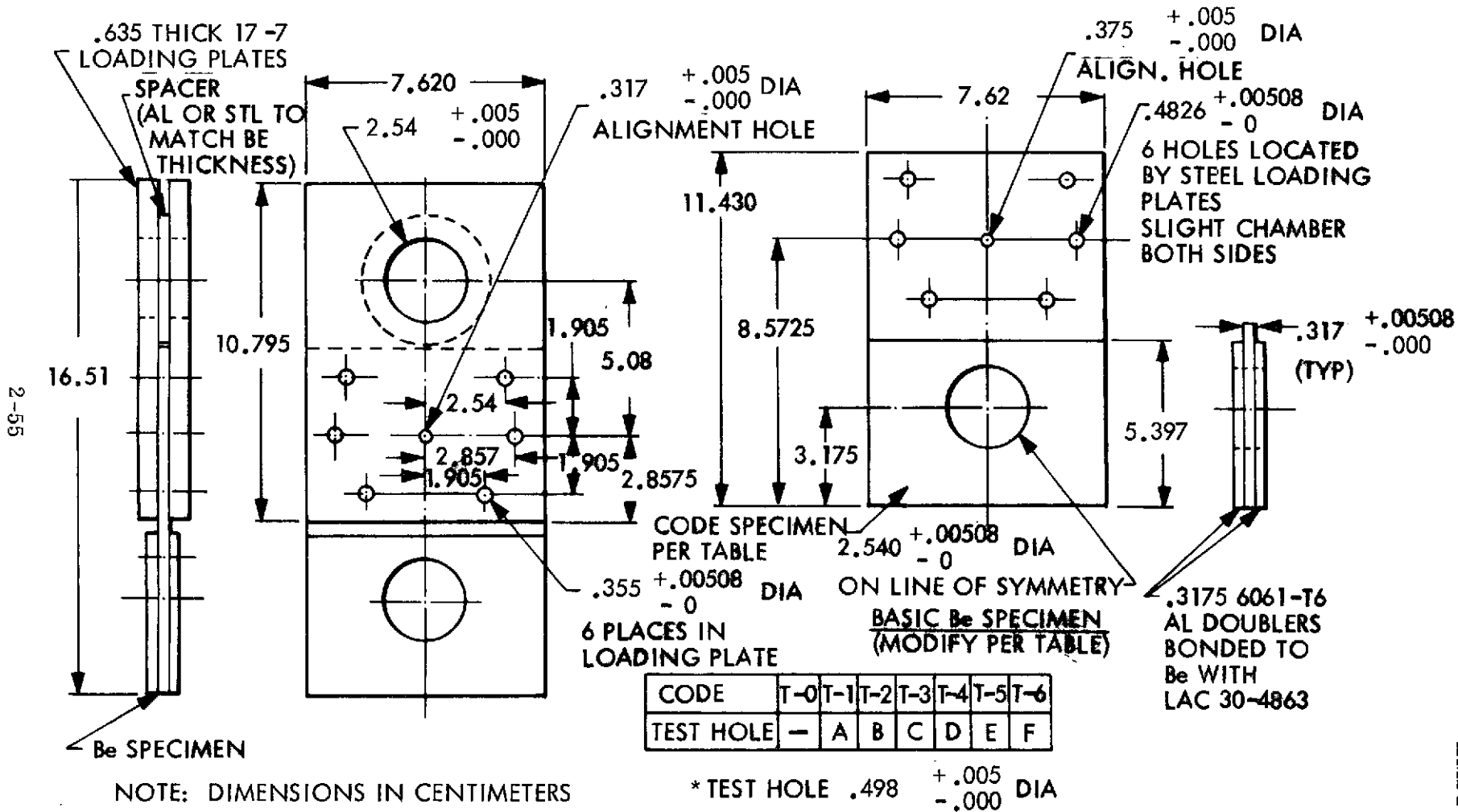Fig. 2.3-7 Squeezing Rivets into Stiffener and Panel

.635 THICK 17-7
LOADING PLATES

SPACER
(AL OR STL TO
MATCH BE
THICKNESS)

7.620

2.54 $^{+.005}_{-.000}$

.317 $^{+.005}_{-.000}$ DIA
ALIGNMENT HOLE

16.51

10.795

1.905

5.08

2.54

1.905

2.857

1.905

2.8575

.355 $^{+.00508}_{-0}$ DIA

6 PLACES IN
LOADING PLATE

Be SPECIMEN

NOTE: DIMENSIONS IN CENTIMETERS

.375 $^{+.005}_{-.000}$ DIA
ALIGN. HOLE

7.62

.4826 $^{+.00508}_{-0}$ DIA
6 HOLES LOCATED
BY STEEL LOADING
PLATES
SLIGHT CHAMBER
BOTH SIDES

11.430

8.5725

3.175

.317 $^{+.00508}_{-.000}$
(TYP)

5.397

CODE SPECIMEN
PER TABLE

2.540 $^{+.00508}_{-0}$ DIA
ON LINE OF SYMMETRY

BASIC Be SPECIMEN
(MODIFY PER TABLE)

.3175 6061-T6
AL DOUBLERS
BONDED TO
Be WITH
LAC 30-4863

CODE	T-0	T-1	T-2	T-3	T-4	T-5	T-6
TEST HOLE	—	A	B	C	D	E	F

*TEST HOLE .498 $^{+.005}_{-.000}$ DIA

Fig. 2.3-8 Test Specimen Assembly (Fasteners Omitted)
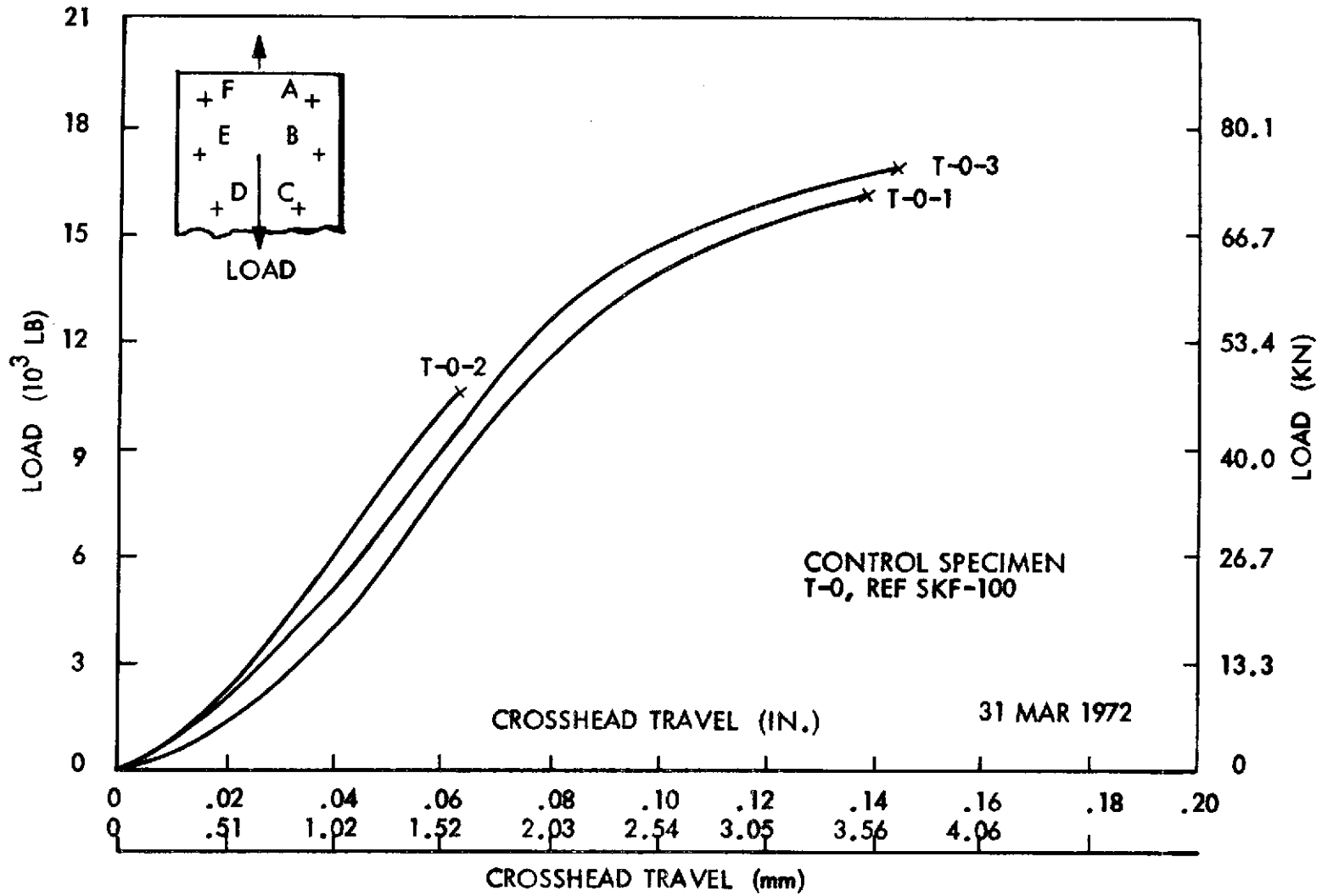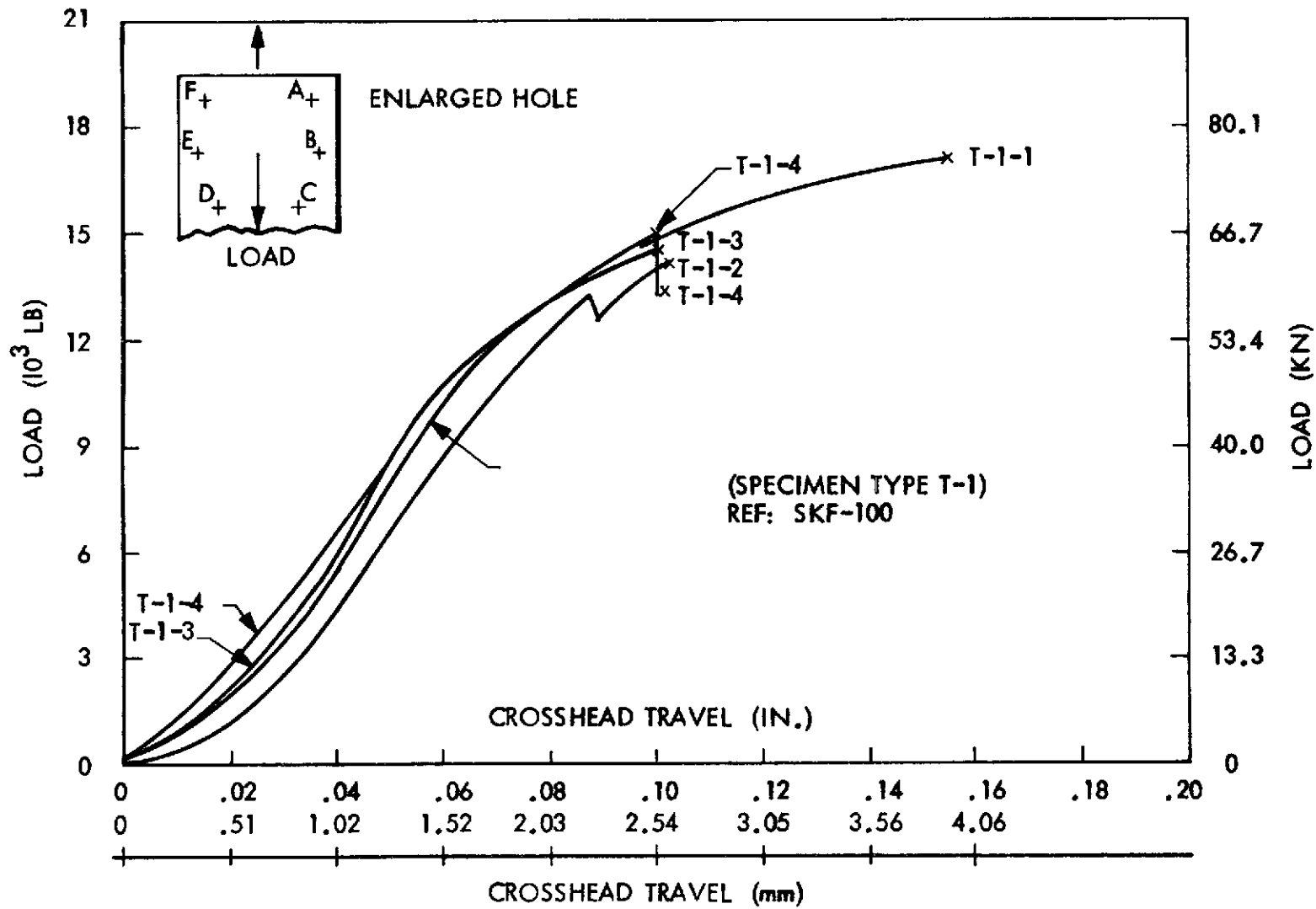
Fig. 2.3-9 Fastener Fit Test for CRS Beryllium
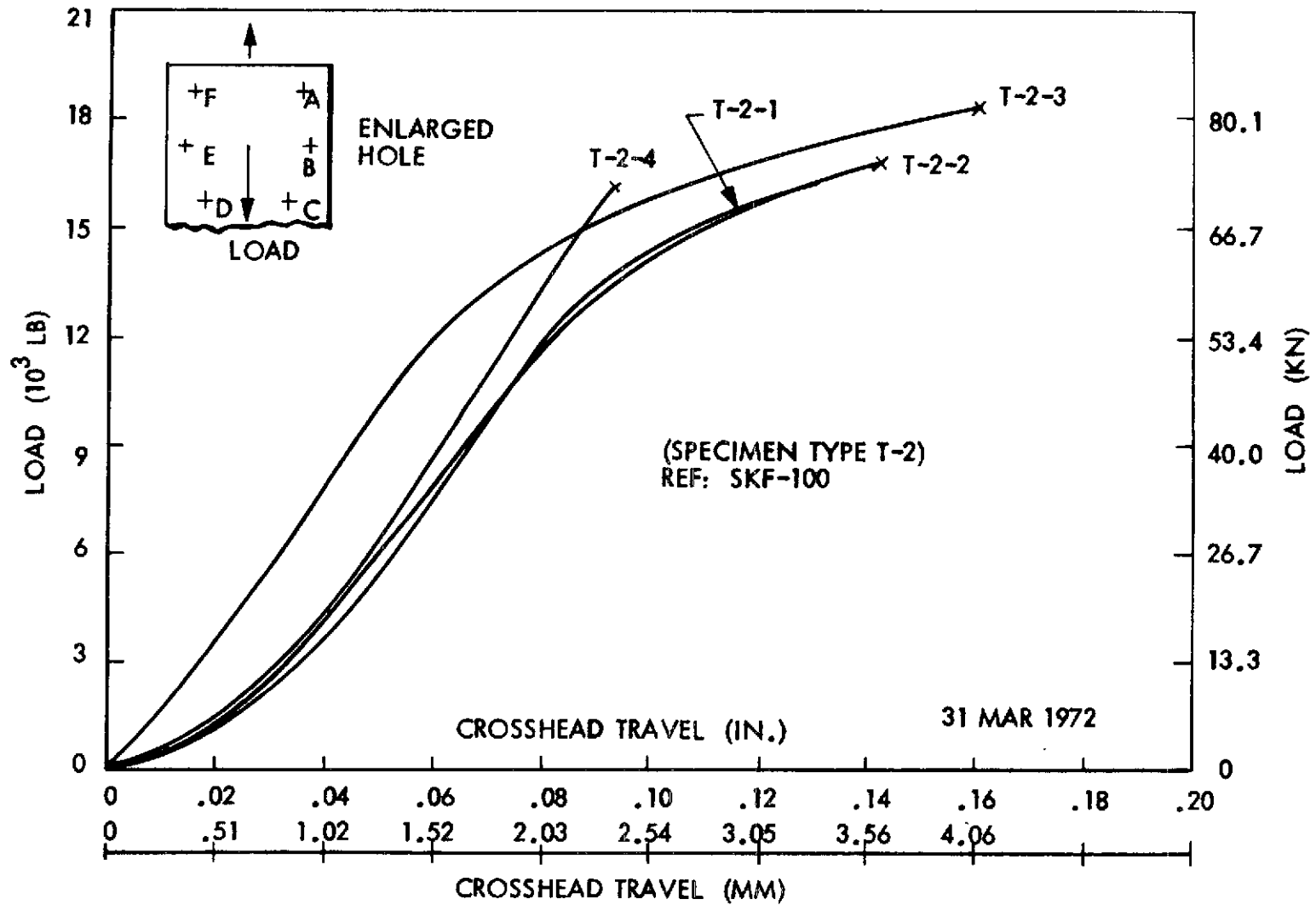
Fig. 2.3-10 Fastener Fit Test for CRS Beryllium
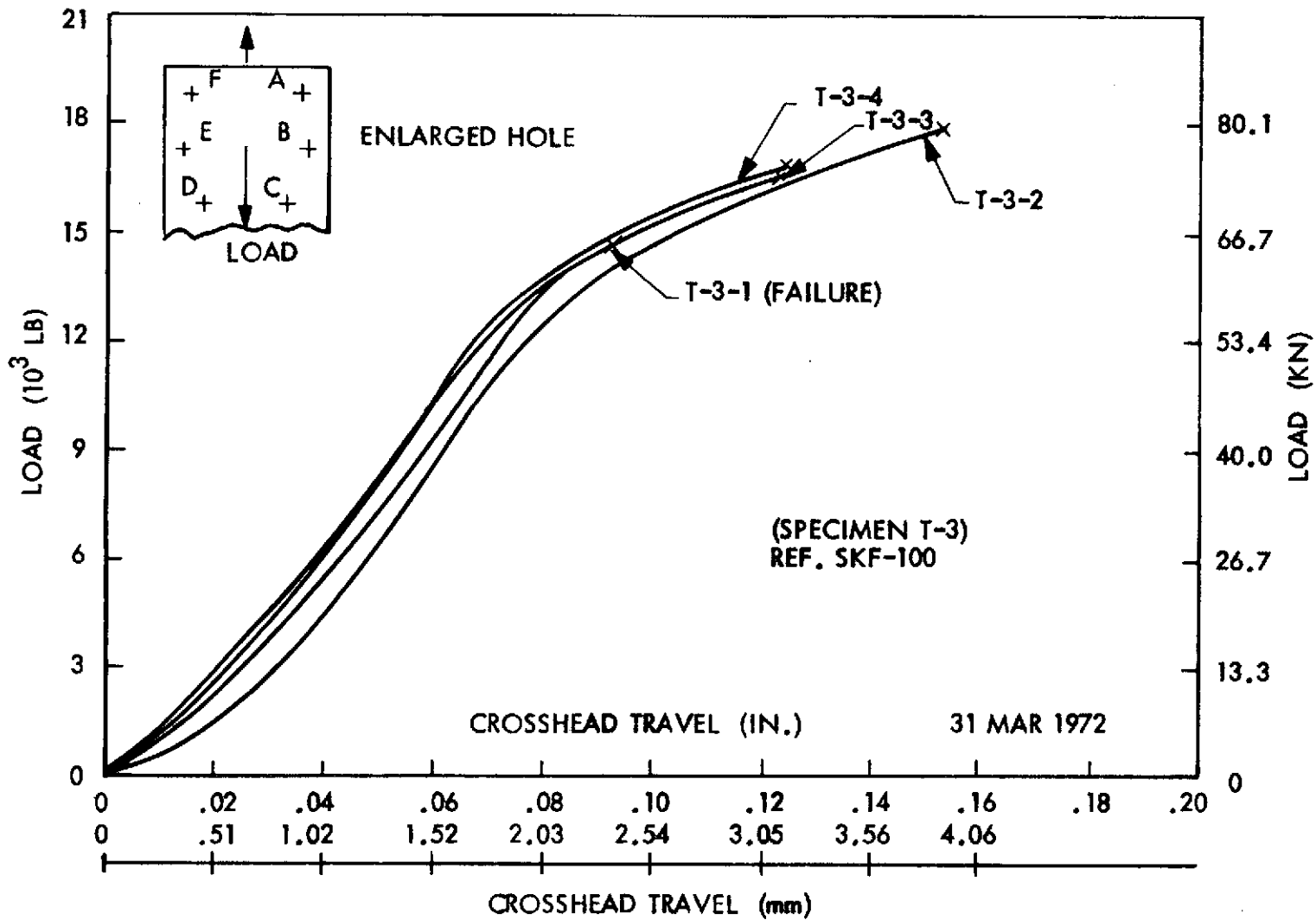
Fig. 2.3-11   Fastener Fit Test for CRS Beryllium

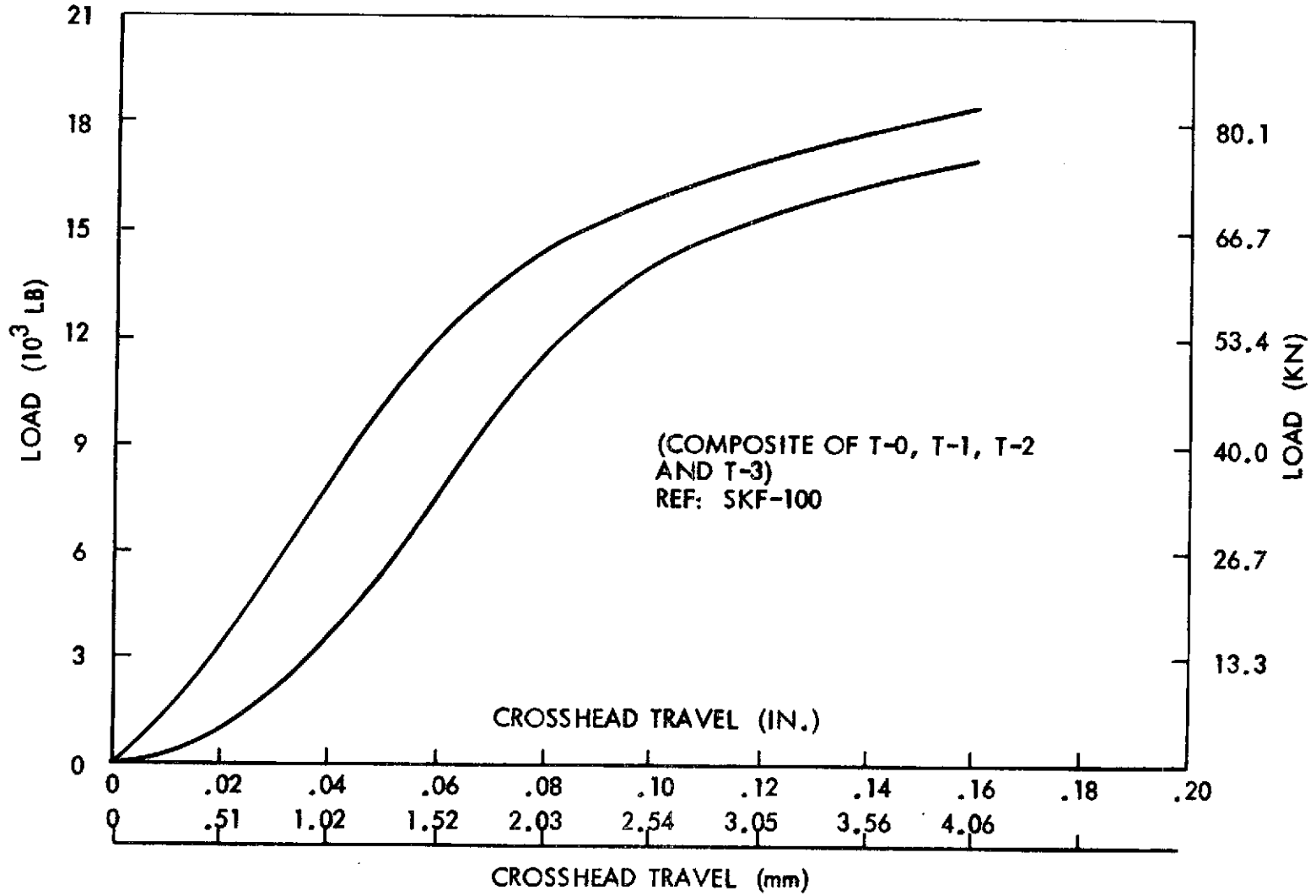Fig. 2.3-12 Fastener Fit Test for CRS Beryllium

Fig. 2.3-13 Envelope — Load Vs Crosshead Travel

loading rate 0.02286 cm/min. (0.009 in./min.), was used throughout to minimize any shock loading effect. It is evident that under static loading conditions, load redistribution over a fastener cluster in cross-rolled beryllium does occur. Specifically in this case, at least 0.01524 cm (0.006 in.) oversize hole for a 0.47625 cm (3/16 in.) fastener within the fastener pattern tested did not degrade the capability of the joint. Based on the amount of deformation at failure, as shown in Table 2.3-2, 0.0127 — 0.0254 cm (0.005 - 0.010 in.) mismatching of some holes in a large cluster pattern would not jeopardize the joint efficiency.

Results of the two development tasks indicated that perfect match-fit of all holes in an assembly using squeezed rivets may not be mandatory in manufacturing. For 0.47625 cm (3/16 in.) diameter rivets, it might be possible to have up to 0.0254 cm (0.010 in.) oversize holes or mismatched positions without degrading the strength level of the assembly. This is somewhat borne out by the result of the subpanel tests where local failure of any rivet was nonexistent.

This phase of development fully met its objective. Confidence in the riveting operation was well established before assembly began. Evaluation of this area of development is presented in Table 2.3-3.

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Table 2.3-2

FASTENER FIT TEST SUMMARY
REF. SKF-100

Specimen	Failure Load		Ultimate Stress [1]		Total Deformation [2]	
	(kN)	(Kip)	(MN/m^2)	(ksi)	(mm)	(in.)
T-0-1	78.3	17.6	339	49.2	3.51	0.138
T-0-2	50.3	11.3	245	35.5	1.60	0.063
T-0-3	74.3	16.7	314	45.5	3.63	0.143
T-1-1	77.8	17.5	332	48.1	3.94	0.155
T-1-2	59.2	13.3	250	36.2	2.59	0.102
T-1-3	65.8	14.8	277	40.2	2.54	0.100
T-1-4	59.6	13.4	256	37.2	2.59	0.102
T-2-1	71.6	16.1	351	50.9	3.20	0.126
T-2-2	74.7	16.8	314	45.6	3.58	0.141
T-2-3	81.4	18.3	392	56.9	4.06	0.160
T-2-4	71.6	16.1	305	44.2	2.36	0.093
T-3-1	65.4	14.7	319	46.3	2.34	0.092
T-3-2	78.3	17.6	334	48.5	3.89	0.153
T-3-3	73.8	16.6	325	47.2	3.12	0.123
T-3-4	74.3	16.7	315	45.7	3.15	0.124

(1) Based on net sectional area at failure point
(2) Total travel of crosshead

Table 2. 3-3

FIT TOLERANCE STUDY

	Exceed Require-ment	Adequate For Program	Improve-ment Needed
Design of Dev. Tasks		X	
Meeting Objectives	X[1]		
Test Specimen Designs	X[2]		
Test Specimen Fab		X	
Test Method		X	
Data Acquisition & Their Application		X	
Application to Current Design	X[3]		
Application to Future Design			X[4]

Notes:

  (1) Information obtained could alter the design approach to beryllium assembly.

  (2) Could be used also to obtain quantitative data.

  (3) Current design did not permit loose fits.

  (4) Need more test data to reduce current constraints on beryllium design.

2. 3. 3 Fluxless Brazing Development

When a design requires a tubular beryllium shape that exceeds available extrusion capability, the designer faces a difficult problem. Those fabrication techniques commonly used for making an equivalent composite section in other metals are either unacceptable or unproven for beryllium. For example, fusion welding, which is so effective for steel or aluminum, yields very unreliable results with beryllium. Built-up sections using mechanical fasteners and corner angles or tees increase weight and cost. Adhesive bonding or soldering can offer only a partial solution if lower strength or reliability is acceptable. Among known joining processes applicable to beryllium, fluxless brazing appears to be the most promising. The fluxless technique is preferred because of the potential hazard due to flux inclusion or residue which may cause an undesirable corrosive reaction with beryllium. Brazing beryllium using flux with zinc

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or aluminum does not develop high joint strength, even when flux removal may not be a problem. A fluxless brazing technique that can develop a shear strength of more than 172.25 MN/m^2 (25 ksi) shear strength can greatly enhance the structural application of beryllium. It is also an essential element of the total manufacturing technology necessary to bring about a broader application of beryllium structures to Space Shuttle.

Originally, as proposed in the Process Development Evaluation Plan (Appendix O), the beam to be fabricated and tested in this development task was to be a plain rectangular tubular section without corner splice members as shown in EM B1-M3-1, Appendix O. The beam was to be tested so as to develop pure shear stress in the brazed joints.

As more information on material and design was generated with program progress, the development plan was modified to incorporate the shape of stiffener channels being produced. A composite shape was developed, with NASA approval, to replace the plain rectangular section originally proposed. The design of the test beam is shown in Fig. 2.3-14. Length of the beam is increased from 50.80 to 55.88 cm (20 to 22 in.) to better utilize materials on hand. This beam is tested as a cantilever beam, putting one channel in compression with the other in tension. The extension member joined to the beryllium gussets provides a 101.6 cm (40 in.) moment arm at test.

Brazing Procedures and Parameters. Of those high strength silver-copper braze alloys suitable for beryllium, the BAg 18 alloy (60 Ag, 30 Cu 10 Sn) appears to be most promising in terms of brazing temperature and strength. It has been known to develop better than 172.25 MN/m^2 (25 ksi) shear strength, when brazing is controlled.

The first approach in establishing the suitable brazing procedures and parameters was unsuccessful at 1042° K $(1400^\circ$ F). At this brazing temperature, BAg 18 showed excellent welting and flow without any significant contact pressure. However, the excellent flow and coverage was more than offset by degradation of joint strength because of the presence of excessive intermetallics. From micrographic studies of the interface zone, the most effective avenue to reduce the formation of intermetallics is to reduce the brazing temperature and time. The lowest practical brazing temperature without elaborate controls appeared to be about 930° K $(1200^\circ$ F). A series

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TEST ADAPTORS

45.72 cm

BERYLLIUM CHANNELS

10.16 cm

BERYLLIUM CAP
PLATES

A

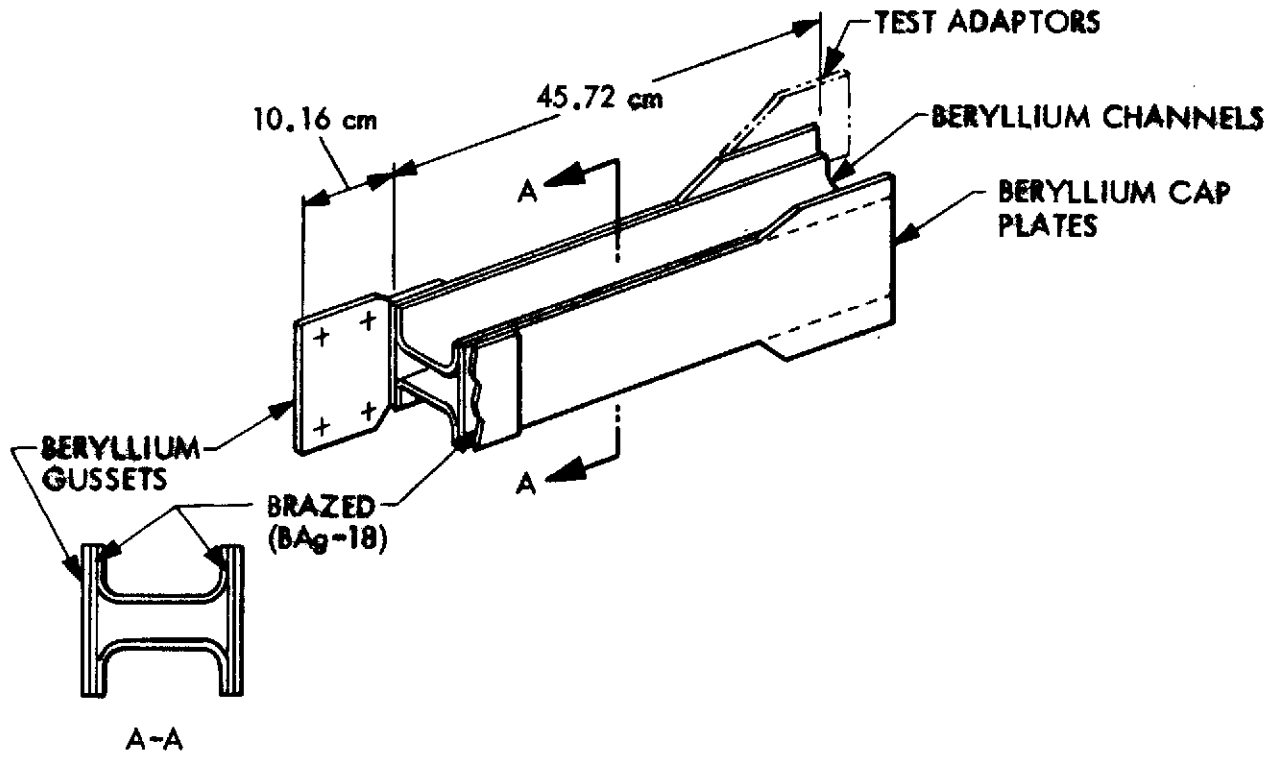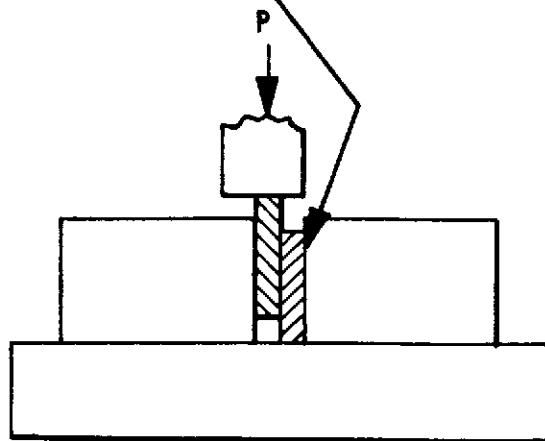BERYLLIUM
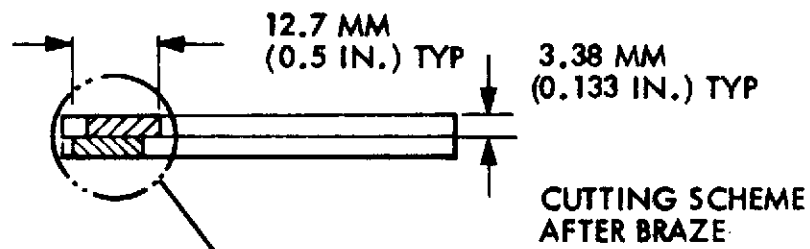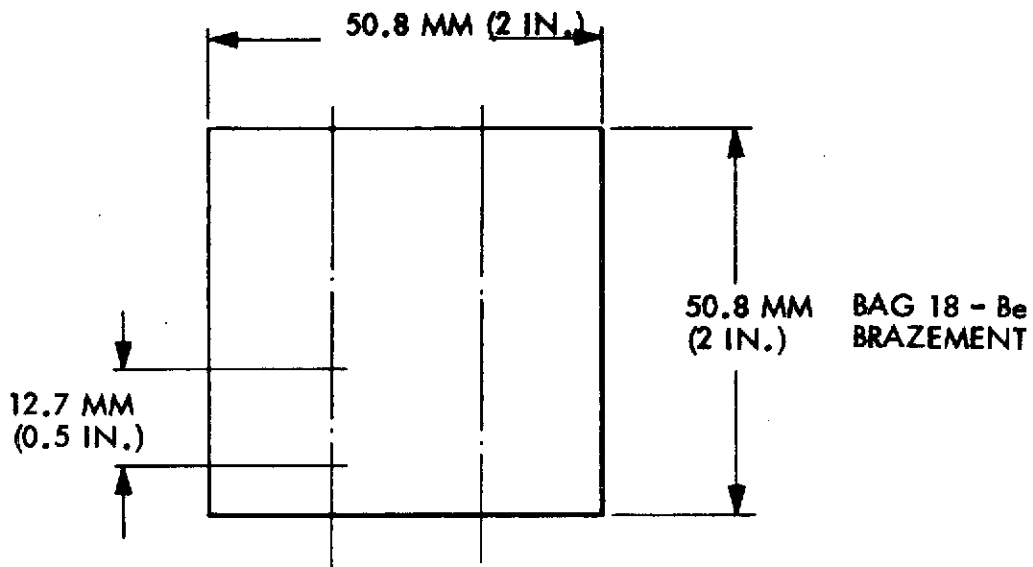GUSSETS

BRAZED
(BAg-18)

A

A-A

Figure 2.3-14 Truss Component Test Beam — Braze Assembly

of tests was conducted at a temperature of 990°K (1300°F) using a contact pressure of about 34.45 N/cm^2 (50 psi) to compensate for minor deviation of component flatness. To reduce material usage and vacuum furnace time, test specimens, as shown in Fig. 2.3-15, were used. At 990°K (1300°F) brazing temperature, 34.45 N/cm^2 (50 psi) contact pressure and a brazing cycle of 10 minutes at temperature, test results showed an average compression shear strength of about 172.25 MN/m^2 (25,000 psi). Better strength may be feasible, but is not required for the design on hand. Additional development is not warranted. This set of brazing procedure and parameters were used to assemble the test beam.

Test Beam Assembly. The technique to braze the test beam assembly is schematically shown in Fig. 2.3-16. All required beryllium components were etched and cleaned immediately prior to their assembly into the retort box. The bottom portion of the retort box was welded together first, leaving the cover sheet unassembled. The components were then assembled using special beryllium rivets to align them and stainless steel spacer bars to support the flanges against the contact pressure during brazing. The assembly was placed on the bottom pressure transfer plate in the open retort box. The top pressure transfer plate was installed, then the cover sheet placed on top of it and clamped in place. The internal assembly was made slightly taller than the net internal height of retort box to keep the assembly under pressure as the retort box was welded tight. A 1.270 cm (1/2 in.) stainless steel tube exited from one end to provide hook-up with the vacuum pump and a source for purging argon gas. This retort box was then placed in a recirculative furnace. After the retort box was purged adequately by argon, it was pumped down to about 10^{-4} torr during the brazing cycle in accordance with the parameters selected. The ratio of the pressure plate to that of the brazed area was such as to develop about 34.45 N/cm^2 (50 psi) contact pressure over brazing zones at one atmosphere condition. The assembly was cooled down to room temperature while vacuum was maintained in the retort. Then the box was cut open to remove the brazed assembly shown in Fig. 2.3-17.

Load Test. The completed beam assembly was tested as a rigidly-mounted cantilever beam, as shown in Fig. 2.3-18, and in accordance with EM B1-M2-6, Appendix I.

50.8 MM (2 IN.)

50.8 MM
(2 IN.)

BAG 18 – Be
BRAZEMENT

12.7 MM
(0.5 IN.)

12.7 MM
(0.5 IN.) TYP

3.38 MM
(0.133 IN.) TYP

CUTTING SCHEME
AFTER BRAZE

P

COMPRESSION SHEAR TEST SCHEME

Fig. 2.3-15 Test Specimen Fabrication

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STAINLESS STEEL 0.76 MM (0.030 IN.)
RETORT, PURGED VACUUM
ENVIRONMENT

BEAM ASSEMBLY

STAINLESS STEEL
SPACERS (TYP)

BRAZED
AREAS

PRESSURE TRANSFER
PLATES, TOP AND
BOTTOM
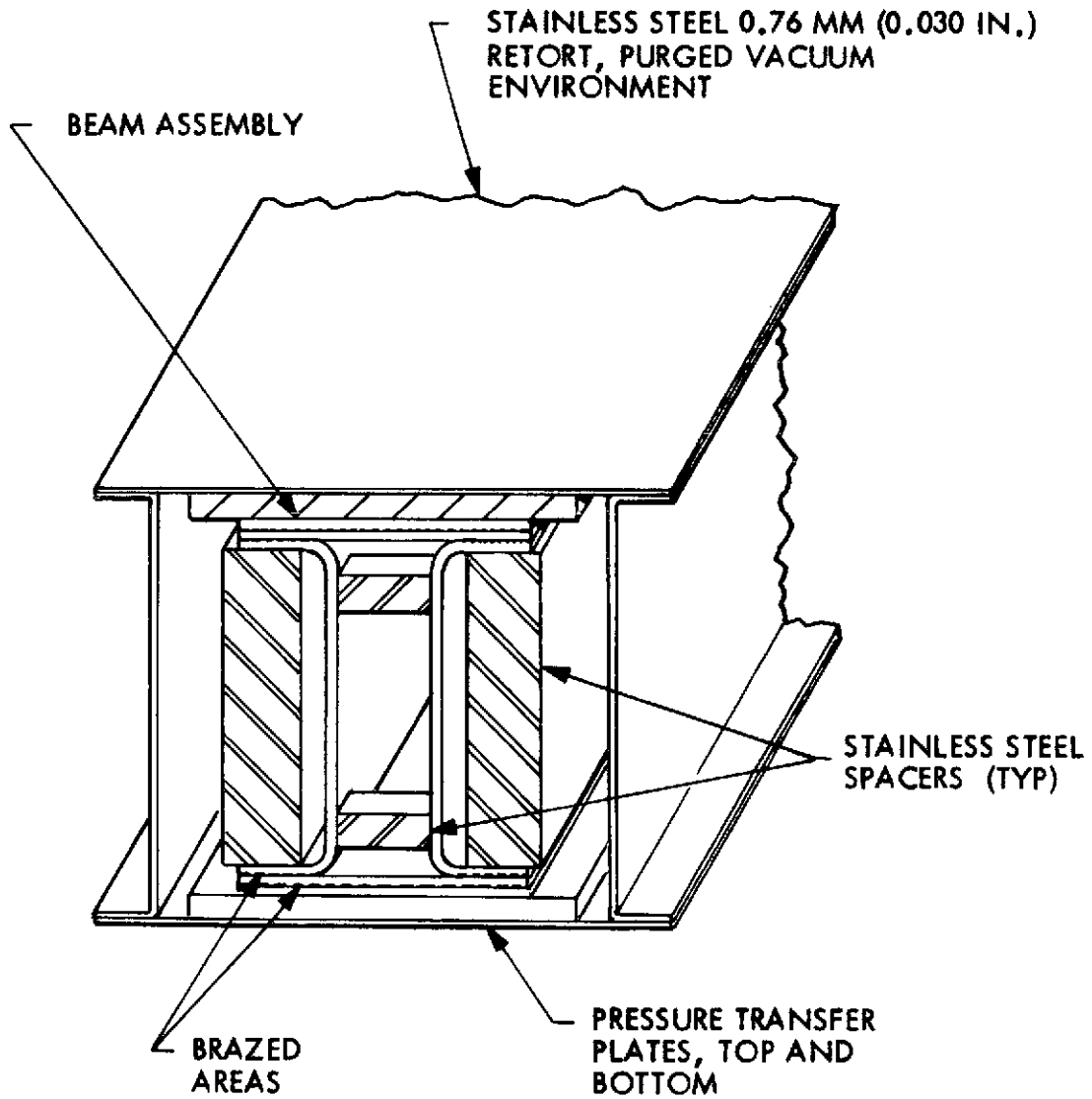
Fig. 2.3-16 Schematic Arrangement, Test Beam
Braze Assembly

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Fig. 2.3-17 Brazed Truss Component Test Beam

STRAIN GAGES
2 REQUIRED

BRAZED ASSEMBLY

V = 6494.08 N
(1460 LB) LIMIT
9073.9 N
(2040 LB) ULTIMATE

35.56 CM
(14.0 IN.) (REF)

45.72 cm (18 IN.)

105.6 CM (40 IN.)

STEEL
MOUNTING
PLATES

STRAIN GAGES
BACK TO BACK
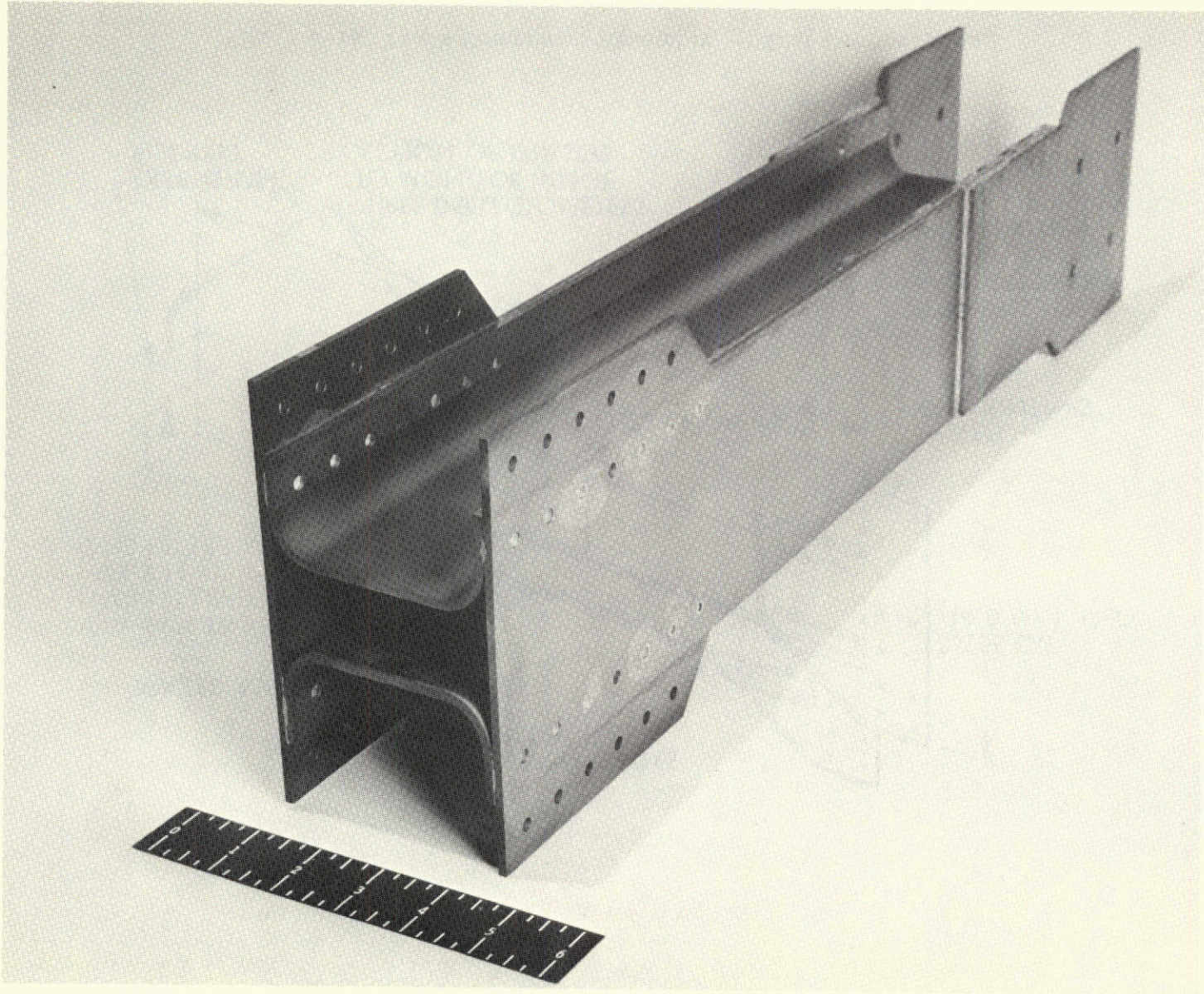BOTH FLANGES
4 REQUIRED

EXTENSION
FOR TEST

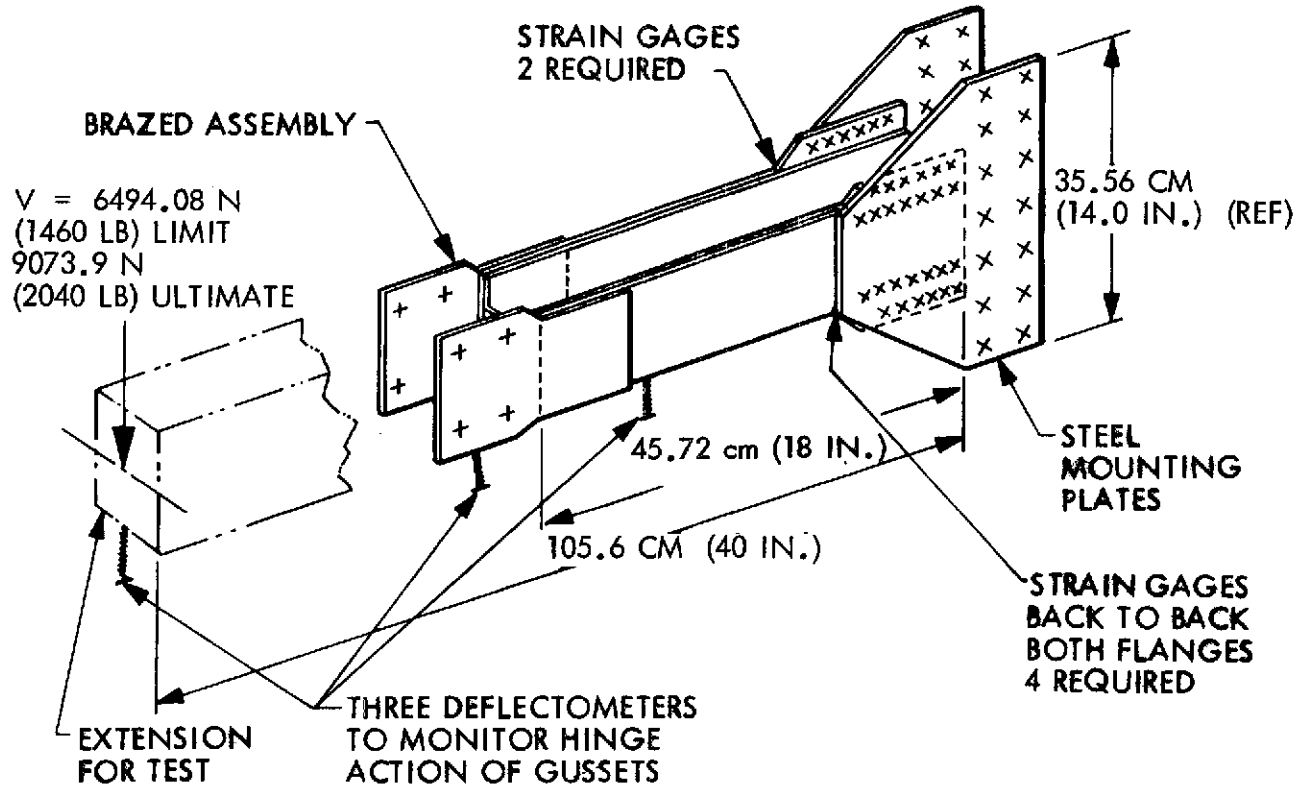THREE DEFLECTOMETERS
TO MONITOR HINGE
ACTION OF GUSSETS

Fig. 2.3-18 Truss Component Assembly — Test Configuration

The beam assembly was tested in the Lockheed Structural Mechanics Test Laboratory at Palo Alto. The results are reported in Section 2.5.1.

2.3.4 Conclusions and Recommendations

The beryllium structures generated in this contract involved many fabrication processes originally developed by LMSC. These are basically current production processes, except in a few cases where some extension of the process was necessary to cope with the larger size components involved. Various structural configurations were produced, ranging from short fluxless brazed tubular members to large complex composite compression panels.

With a disciplined approach to process development, which was planned and coordinated with design and fabrication requirements, new process data acquired were applied in a timely manner. Therefore, no unresolvable problems were encountered throughout the fabrication phase. Since the structural designs selected typified most of the significant applications of beryllium for space structures, it can be concluded that not only is manufacturing technology now available but also sufficiently established to meet any mechanically assembled compression structures that affectively utilizes beryllium.

To further the effectiveness of beryllium as a candidate material for structures, not only the cost of raw material but also the cost of manufacturing should be reduced. The area that offers highest potential for manufacturing cost reduction lies in the exacting assembly procedures now prevailing. Based on the fit-tolerance investigation, the match drill/disassemble/etch routine, now in practice, might be greatly relaxed to reduce cost. Also, broader application of brazing (flux and fluxless) technique can enhance design flexibility as well as manufacturing economy. Towards this goal, the following recommendations are made:

1. Determine manufacturing limits on fit-tolerance vs fastener spacing and D/t ratios.

2. Determine the acceptability of reamed fastener holes without additional etching (stress relieve) prior to final assembly.

3. Develop better techniques (manual and furnace) for brazing (flux and fluxless) applicable to complex 3-dimensional structures.

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2.4 PHASE IV — FABRICATION

The specific items manufactured were as follows:

- All of the beryllium test coupons used in Phase I, Materials Evaluation
- All of the necessary hardware used in Process Development, Phase III
- One Uniform Load Subpanel
- One Concentrated Load Subpanel
- Two Truss Component Assemblies
- One NASA/MSFC Uniform Load Panel
- One NASA/MSFC Concentrated Load Panel

The effort involved in manufacturing the two subpanels and the two full-size panels was extensive but did not invoke any untried processes. Only in two areas, where additional refinement on known processes were required to assure first trial success, was there any concern. One area was in the thermal forming of the long stiffener channels and the other was related to the technique and control of squeezing a large cluster of rivets. The scope of the development conducted and the results achieved are reported in Section 2.3, Phase III — Process Development. Process Development, Phase III, was closely integrated throughout the manufacturing phase. The overall process plan applied to all panels is depicted in EM B1-M4-3, Appendix R.

2.4.1 Material Preparation

In accordance with LMSC's established procedures, and to strive for optimum usage of raw material, all sheet stock received was inspected, thickness checked and identified. These sheets were then numbered and predetermined cutting patterns were appropriately transferred onto the respective sheets, in accordance with EM B1-M4-2, Appendix Q. Cutting was accomplished by the 35.6 cm (14 in.) diameter abrasive cutting wheel.

To maximize yield potential on raw material, the largest blanks, such as those for the panels and doublers, were cut first. Detail work such as drilling was then

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performed before other blanks were cut. This was to provide added insurance to recoup material in case of accidental damage in drilling the panels. Should that occur, the defective part could be salvaged for smaller blanks. All beryllium manufacturing activities were performed in the special beryllium facilities located in Bldg. 170.

2.4.2 Tooling

Because this is a development contract, with its primary objective aimed at establishing manufacturing technology feasibility and availability, costly production types of permanent tooling was not used. Lockheed's experience has shown that for this type of development work, it is most cost effective to use the most experienced and highest skilled operators with simple templates and "one-shot" tooling which could be readily modified and reworked to adjust for any unexpected requirements that may develop. Therefore, only two types of toolings were used, (1) a universal thermal forming die for all "c" channels and (2) a set of flat drill templates.

Thermal Forming Die. The evolution of the thermal forming die from design to tool trial is reported in Section 2.3.1 (Phase III). This die was installed in a 4-post Hennifin 200 ton hydraulic press equipped with a 145 cm by 264 cm (57 in. by 104 in.) bed. LMSC acquired this press especially for a range of beryllium work. It has an unusually large shut height to accept very thick hot dies. Because of this feature, it was necessary to use a deep I-beam to mount the upper half of the forming die to the upper platen. Asbestos curtains were draped all around the die to minimize heat loss. Individual controller panels were used to control each set of the electrical heating elements in the die.

Templates. Since the number of individual detail pieces requiring drilling was very low, hardened drill templates were not necessary. In most cases, the hole pattern in the drill template was used only once, and no significant wear of these templates was expected. Therefore, plain steel and aluminum thin-gage drill templates were used throughout. Using undersized holes to start, the first piece of beryllium drilled.

was used to transfer the hole pattern to another piece, and so on. The holes in the "c" channel were matched-drilled with the subpanels. This approach held the number of drill templates to a minimum.

2.4.3 Forming

As reported in Phase III, since the operational characteristics of the forming die were determined, the forming operation became somewhat routine, although there were a few events worth noting.

At the beginning, because of the length involved, locating pins at both ends and the center of the die were provided to hold the blank in position while resting on the bottom form block (male). Later, when it was discovered that absolute restraint of the blank was undesirable and harmful, it was allowed to float slightly to adjust itself while entering the die. The shift was quite small; nevertheless, extra width had to be allowed in the blank for trim.

After all the thin-gage materials were successfully formed, the die was reworked to accept the thicker gage material. It was noticed then that the anchoring pins for the female form blocks were deformed, allowing the blocks to spread slightly. New and larger pins were installed. Considerable pressure was required to form the thick-gage channels, either because of slight misalignment in the die or the mounting of it. This excessive pressure began to introduce undesirable deflections in the upper half of the forming die and caused some very severe cracks in the ceramic bolster platen. This was then replaced, as described in Section 2.3.1, and the forming operation resumed without significant problems. Noticeable die wear became evident and the channel did not close completely. These few channels were then hot sized by setting each on its side and using the forming blocks to bring the open leg into dimension.

The hot-forming press with adjacent cooling tube is illustrated in Fig. 2.4-1. As-formed channels are shown in Fig. 2.3-3.
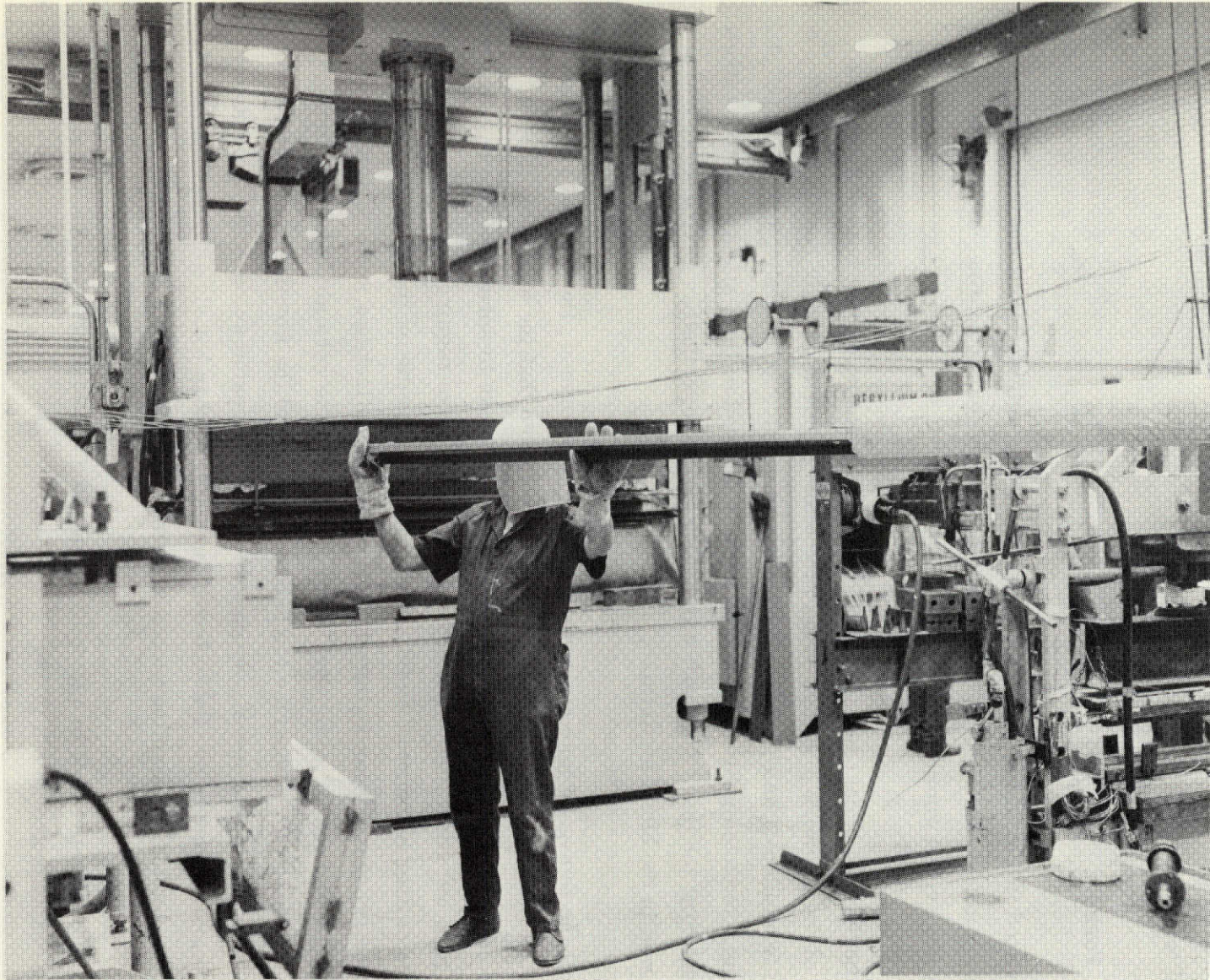
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Fig. 2.4-1 Hot-Forming Press and Insulated Cooling Tube

LMSC-D159319

2.4.4 Detail Fabrication and Assembly

Standard shop practices and procedures were used throughout. The drilling operations on all individual components were accomplished with tornetic units that control both thrust and torque during the drilling cycle. Special LMSC-developed drills were used throughout.

All machined surfaces were given a standard etch to relieve machining stress. Extra long pieces were etched end-over-end to accommodate tank depth. This required skill, but eliminated the extra cost of making temporary etching troughs. Figure 2.4-2 illustrates the employment of EDM machining to finish the stiffener ends.

All pieces were assembled with squeezed monel rivets. To maintain a constant squeezing force for each size of rivet as previously established in the development phase, a modified hydraulic ram and rigid anvil were used for all riveting operations. Figure 2.3-7 shows the equipment and setup used. No significant problem was encountered. Assembled subpanels are shown in Figs. 2.4-3, 2.4-4, and 2.4-5.

2.4.5 Full-Size Panels Assembly

The assembly operation on the two full-size panels was closely patterned to that used successfully on the subpanels. The sizes of these full-size panels were still well within a manageable size for bench top work. Commonly used rigid assembly fixtures applicable for production were not used; relying on the skill and experience of the operators, constant checks on alignment and movement were made to avoid any unnoticed shifting of parts. Furthermore, the gentle action in squeeze-riveting, as compared to impact-riveting, reduced the risk of any tendency of displacing parts clamped in place for assembly purposes. Since the gages involved were relatively thick, as compared to the modulus of the material, damage due to accidental un-balanced handling of a large sheet was much less of a possibility than with very thin material. In summary, no unusual assembly problems were encountered. Assembled full-size panels are shown on the frontispiece and in Figs. 2.4-6 and 2.4-7.
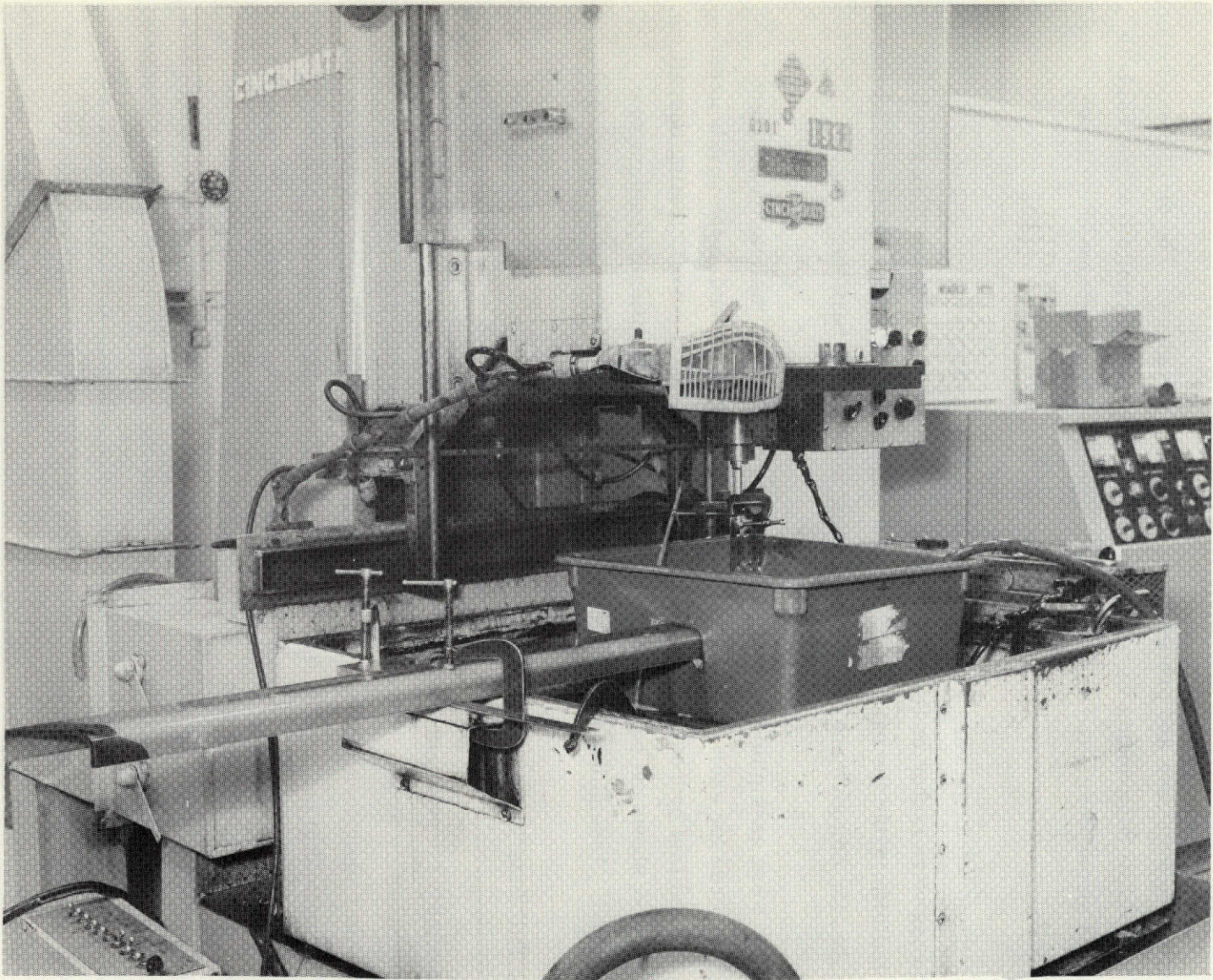
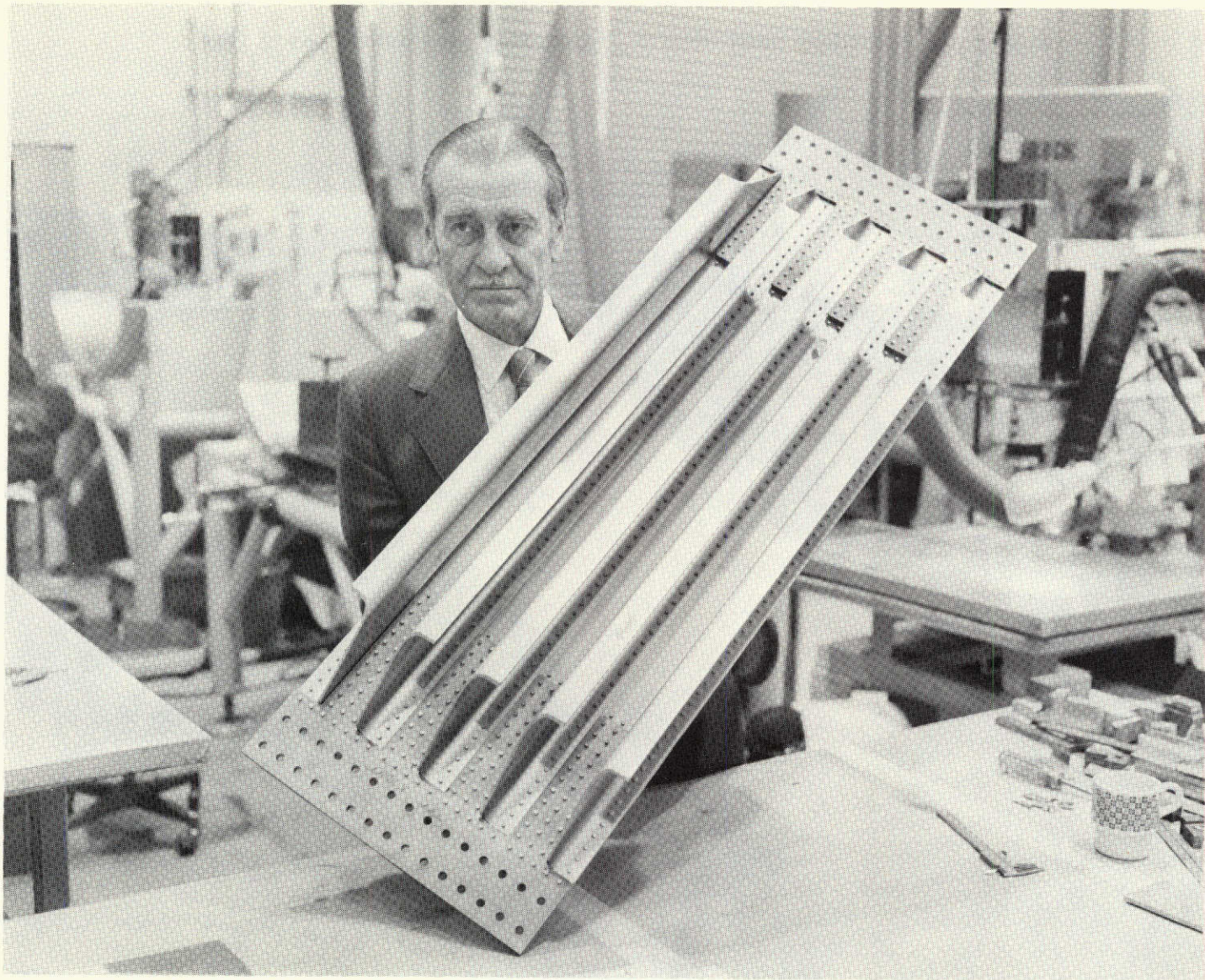Fig. 2.4-2 Cutting Ends of Stiffeners With EDM Machine

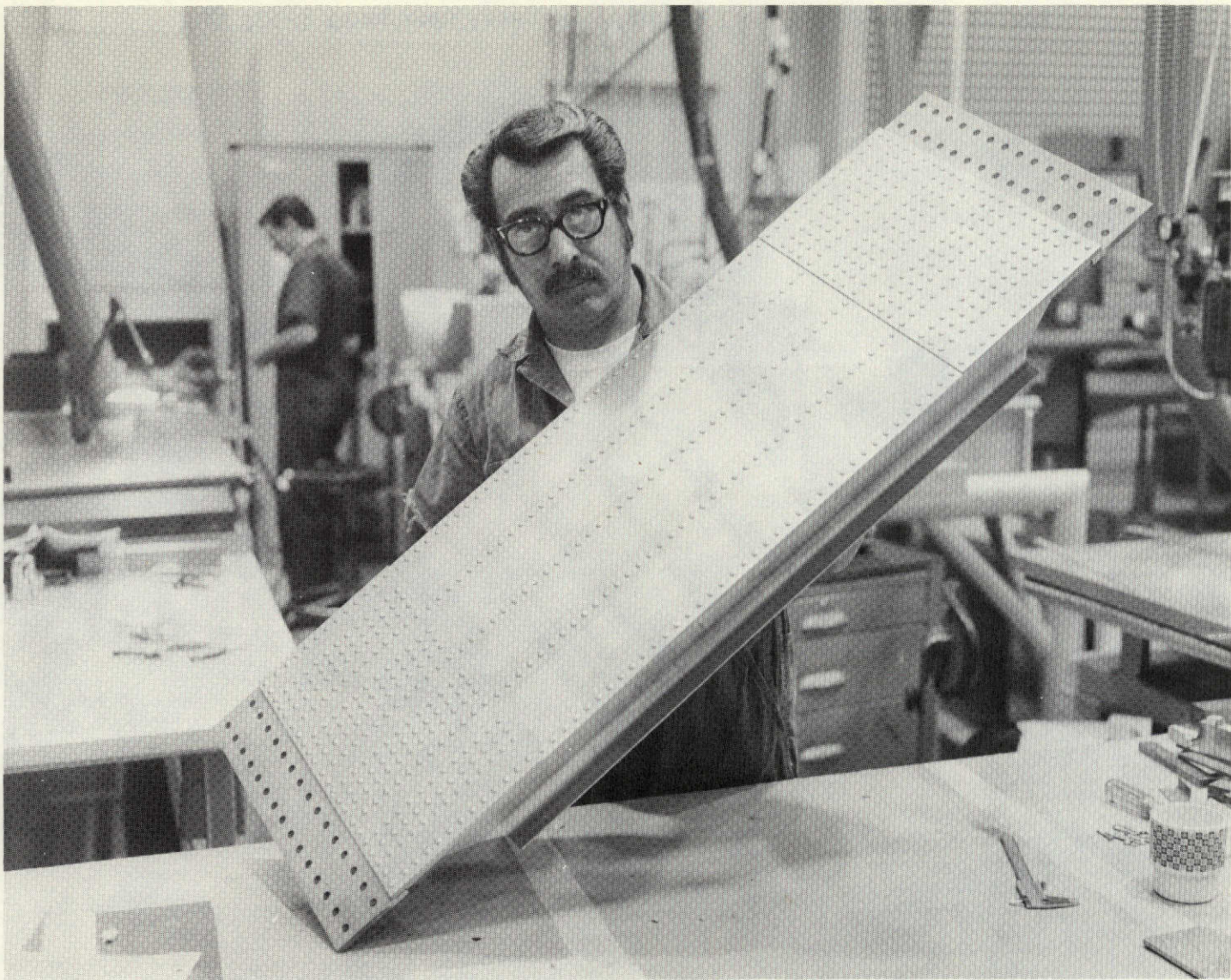Fig. 2.4-3 Completed Assembly, Uniform Load Subpanel, SKJ 201004

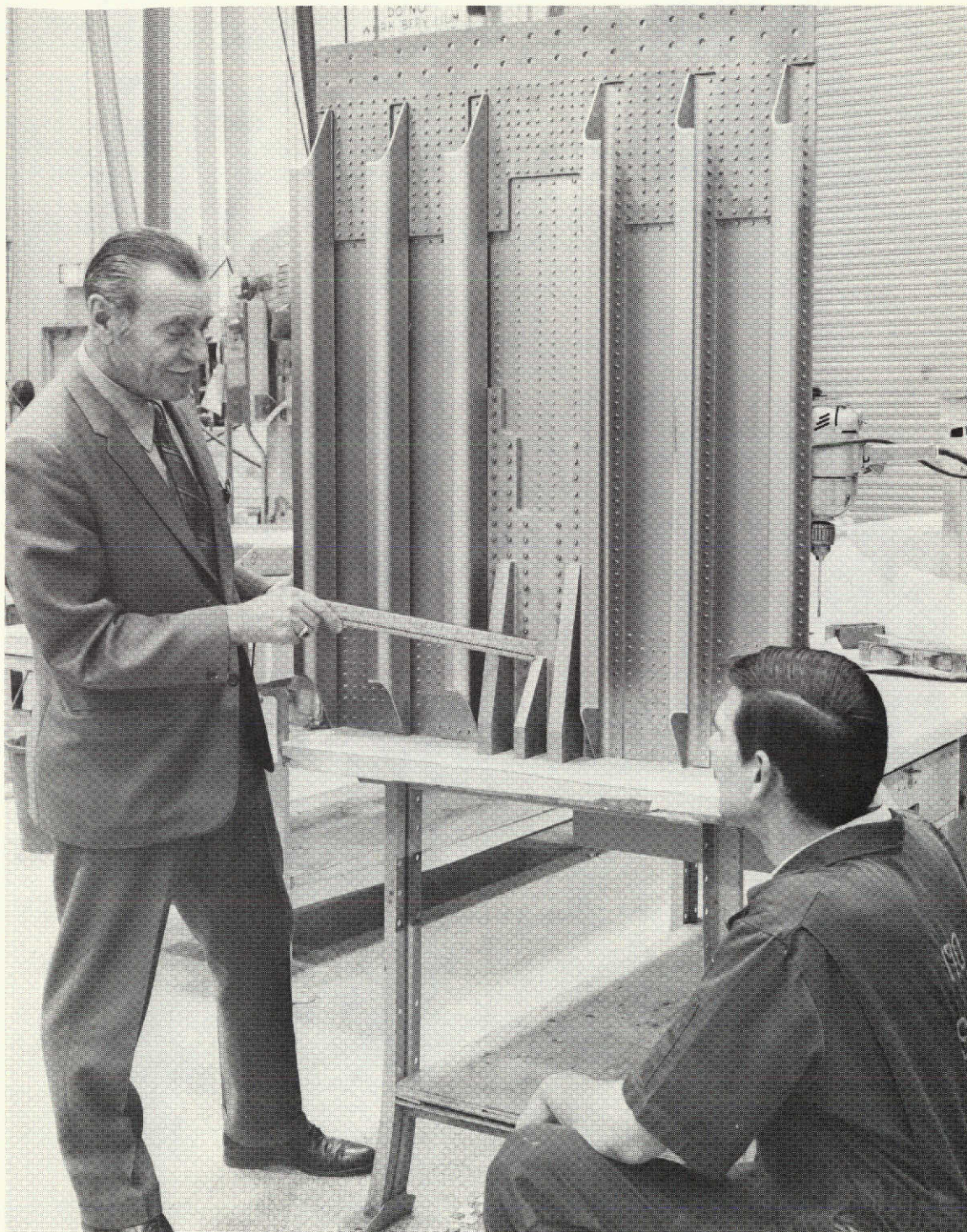Fig. 2.4-4 Completed Assembly, Uniform Load Subpanel, SKJ 201004
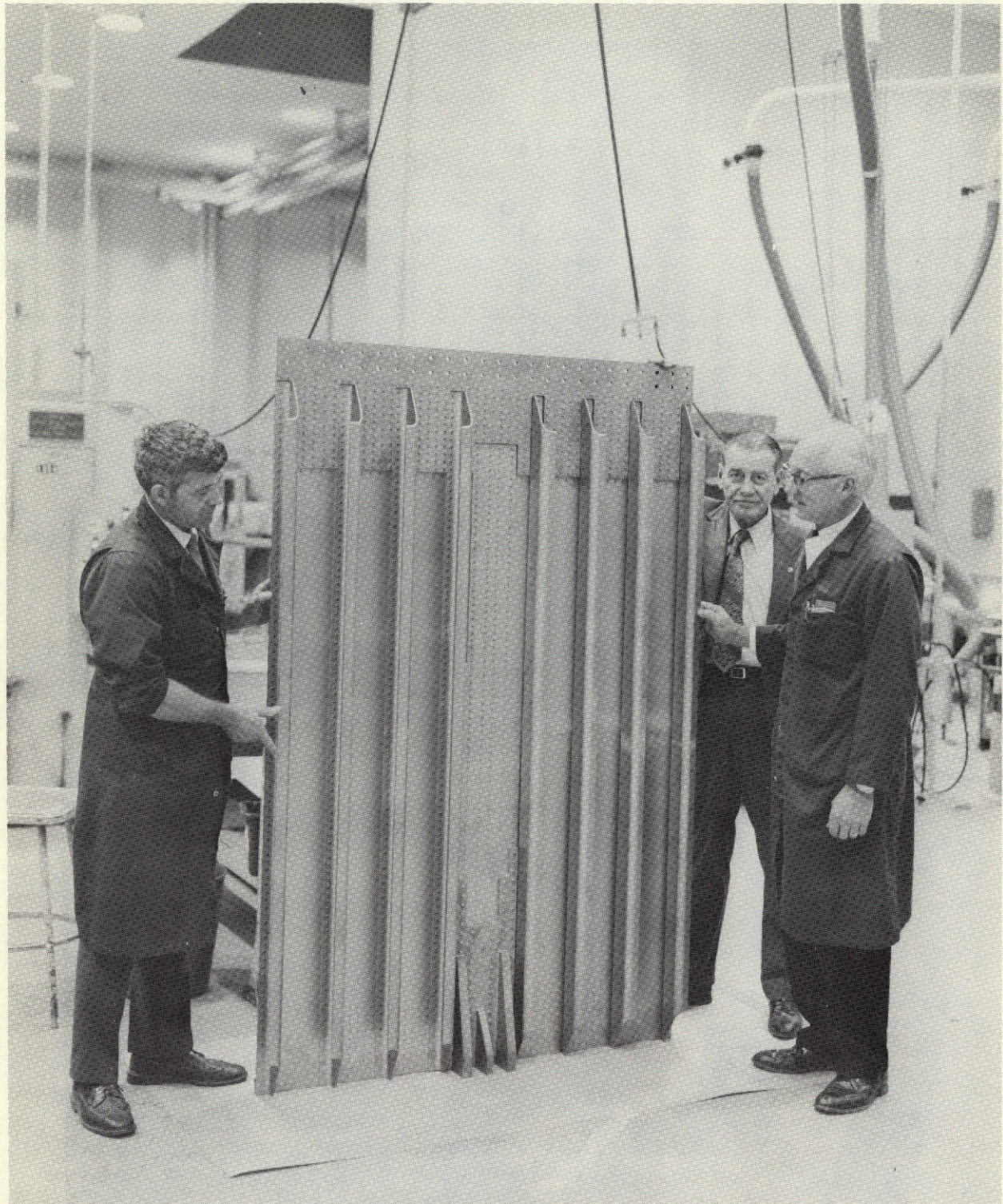
Fig. 2.4-5 Concentrated Load Subpanel SKJ 201007

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Fig. 2.4-6 Concentrated Load Panel SKJ 201001, Rev. A

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Fig. 2.4-7 Uniform Load Panel SKJ 201002

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2.4.6 Quality Assurance

To ensure that the resulting hardware was in compliance with the engineering requirements set forth in the drawings, quality controls were generally exercised as stated in EM B1-M4-4, Appendix S, at a number of points during the manufacture of the beryllium test panels. Longitudinal and transverse tensile coupons were removed from each sheet of the beryllium material order for verification of the mechanical properties required by specification. The results are presented in Section 2.1 of this report. The tools fabricated for this program, and the detail parts subsequently formed on these tools, were subjected to dimensional inspection. Etching was employed to identify cracks after all forming, milling, and drilling operations.

The assembled panels were dimensionally inspected prior to shipment. As a result of this inspection, both panels were accepted as being fully qualified to perform to engineering requirements.

2.4.7 Conclusions and Recommendations

Outside of the two areas of process requirements described earlier, the manufacturing technology involved in the manufacture of the two full-size panels was within LMSC's established capability and experience.

The result of fit-tolerance study indicated that the more costly matched-hole assembly approach may well be modified and that interchangeability is quite feasible. The feasibility of separately fabricating the details, using them interchangeably, should be investigated, including the level of tolerances acceptable for randomly-reamed holes without etching at assembly.

2.5 PHASE V — TEST AND EVALUATION

The purpose of this phase of the program was threefold in nature:

- Establish confidence in design details and analytical techniques
- Verify fabrication and assembly processes
- Demonstrate the structural capability of the contractually required panels

Because of prior experience in beryllium design applications and the knowledge that conventional analytical methods applied to beryllium structures, it was not necessary to evaluate the detail structural response of discrete forms or parts. This led to the development of test panels that were complete subpanels, duplicating the design details of the deliverable panels. This approach also had the additional advantage of surfacing the inevitable design compatibility errors prior to the construction of full-scale panels. Results and objectives of major program tests are discussed in the following paragraphs.

2.5.1 LMSC Testing

As a result of the program approach outlined previously, this phase of testing, involving complete subpanels on components, had the following objectives:

Uniform Load Subpanel Test

- Verify analysis
- Verify end attachment (rivet) capability
- Verify transition from end fitting to skin-stringer panel
- Verify freedom from local effects that might precipitate failure
- Verify strength capability of panel and material
- Verify attachment of skin to stringers
- Verify compatibility of materials for a $316^{\circ}C$ ($600^{\circ}F$) environment

Concentrated Load Subpanel Test

- Verify analysis
- Verify load distribution from concentrated load fitting to panel

- Verify uniform takeout end attachment capability
- Verify transition from uniform takeout fitting to skin-stringer panel
- Verify freedom from local effects that might precipitate failure
- Verify compatibility of materials for a $316^{O}C$ ($600^{O}F$) environment

Testing emphasized the structural integrity aspects of the test items; hence, the instrumentation requirements were limited rather than being extensive, as would be the case for research and diagnostic oriented testing. All strain gages and thermocouples were designed for use in the test temperature ranges selected; all were temperature compensated; and all performed satisfactorily.

The test items were as follows:

(a) One uniform load subpanel, SKJ 201004

(b) One concentrated load subpanel, SKJ 201007

(c) One truss component

Testing of the subpanels [Items (a) and (b)] was conducted in the Structural Test Facilities of LMSC at Sunnyvale, California. The truss component testing was conducted at the Palo Alto Research Test Facility of LMSC. All test objectives were achieved, thereby assuring the structural integrity of the designs and test hardware submitted to NASA/MSFC. In the following discussion, details of each test are presented, together with an evaluation of the test results.

Uniform Load Subpanel, SKJ 201004. Testing of this panel was started on 17 April 1972 after a period of strain gage and thermocouple installation, and fixture preparation. The gages and side supports were installed per the Drawing SKJ 201004, Appendix U. The gages used were BLH Electronics, Inc. strain gage type HT-812-4B-S6, which incorporate a chromel-alumel junction on the gage carrier, temperature compensated. Two ceramic cement cure cycles to $316^{O}C$ ($600^{O}F$) were used to install the gages, one for cement precoat and the second for the cement cover coat. The titanium end fittings on the panel were fitted with a pair of steel load-bearing angle brackets. This prepared specimen was then installed in a Baldwin 440,000-lb

universal test machine. Heating the specimen to the required temperatures was accomplished by means of two quartz tube heater reflector arrays, one on each side of the test specimen. Each array had separate controls. The complete setup is shown in Fig. 2.5-1. Panel arrangement was similar to that shown in Fig. 2.5-4.

The testing was conducted according to the requirements specified in EM B1-M2-6, Appendix I. All strain gage and load data were read out on a Brown Engineering Automatic Data Acquisition System, while thermocouple data were recorded on a Honeywell Multipoint Strip Recorder. The following tests, in sequence, were successfully completed between 17 and 20 April:

1. Room temperature test to 50 percent limit load
2. Room temperature test to 100 percent limit load
3. Elevated temperature test to 50 percent limit load
4. Elevated temperature test to 100 percent limit load
5. Elevated temperature test to 140 percent limit load, hold for 10 seconds and continue loading to failure

Failure occurred at approximately 200 percent limit load at 725,900 N (163,200 lb) compression. Figures 2.5-2 and 2.5-3 show the failed specimen.

No significant problems were encountered in testing this subpanel. A minor difficulty was experienced in trying to achieve a uniform temperature distribution throughout the test specimen in the first portion of the elevated temperature tests. A longer soak time solved this difficulty..

An evaluation of the test results is documented in EM B1-M5-1, Appendix T. The measured stresses compared favorably with the predicted stresses in all the tests except the 140 percent limit load test. Five gages were reading above the compressive yield stress at this loading, indicating that yielding and redistribution of loading was occurring. Prior to collapse of the panel, at 200 percent limit load, 17 of the 19 gages were reading strains in the plastic range of the material, indicating extensive redistribution of loading in the panel, and this was evident in the appearance of the
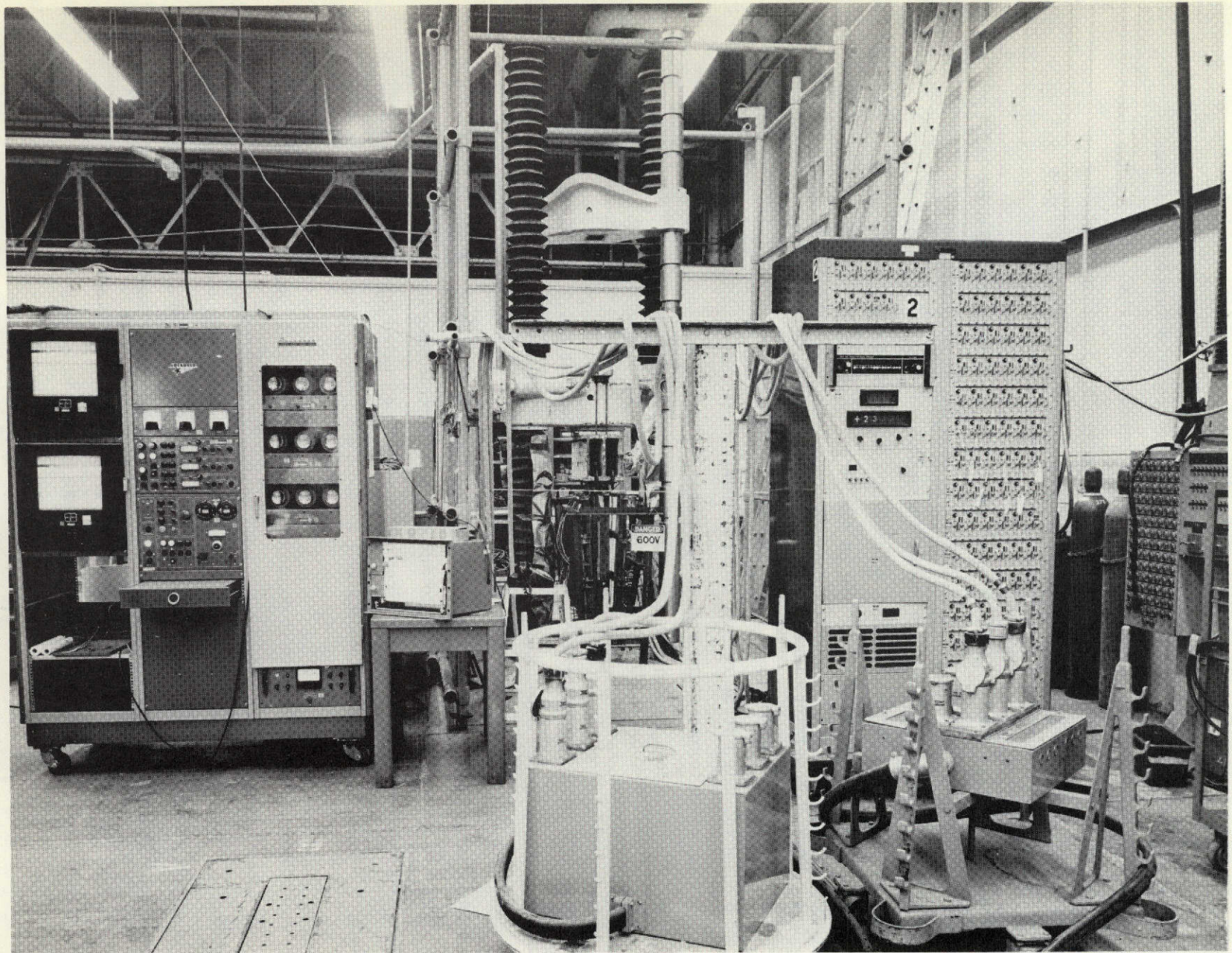
LMSC-D159319

Fig. 2.5-1 Panel Test Setup Showing Test Machine Specimen in Heating Arrays,
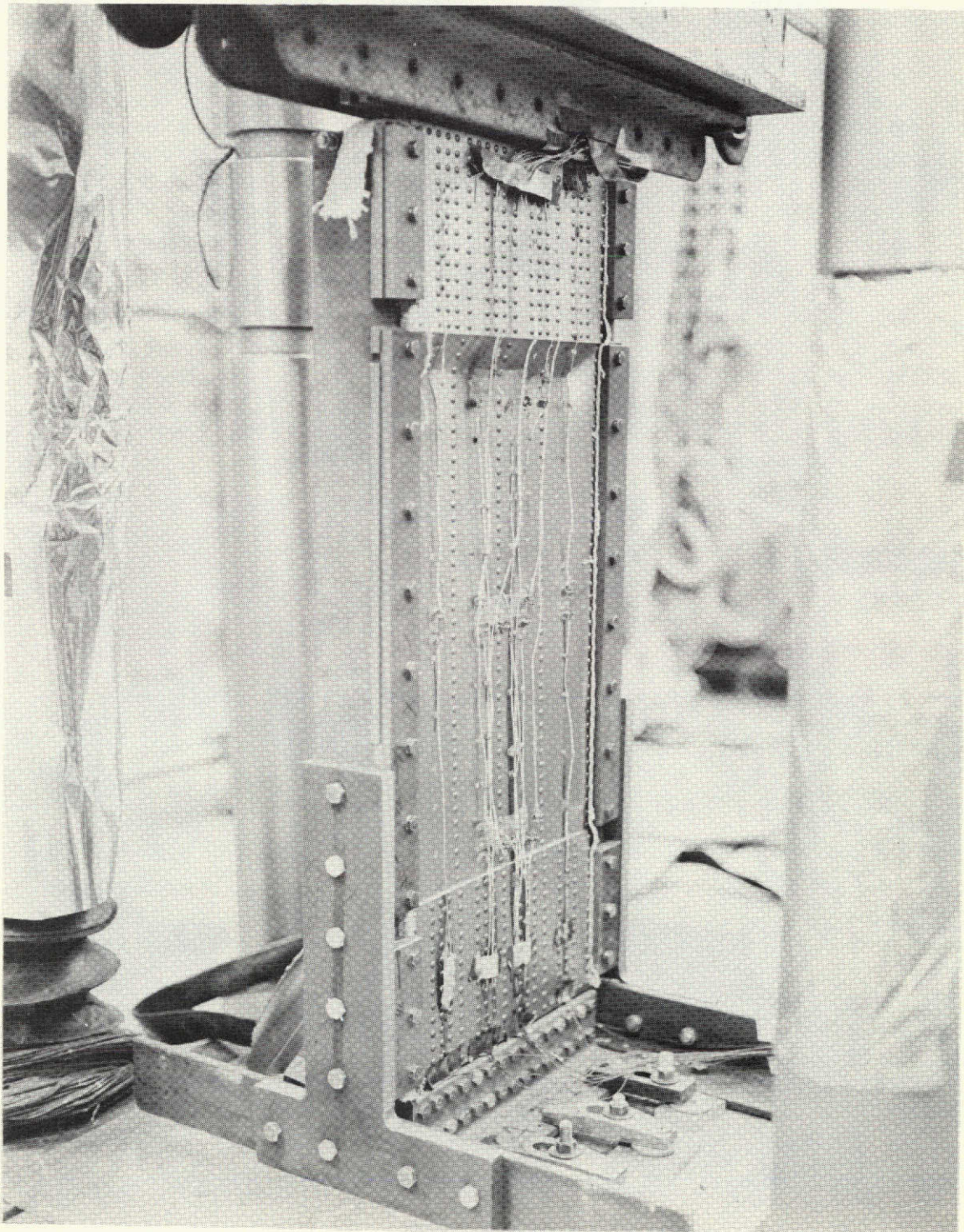Controls, and Temperature Recorder

Fig. 2.5-2 Uniform Load Subpanel SKJ 201004 After Testing

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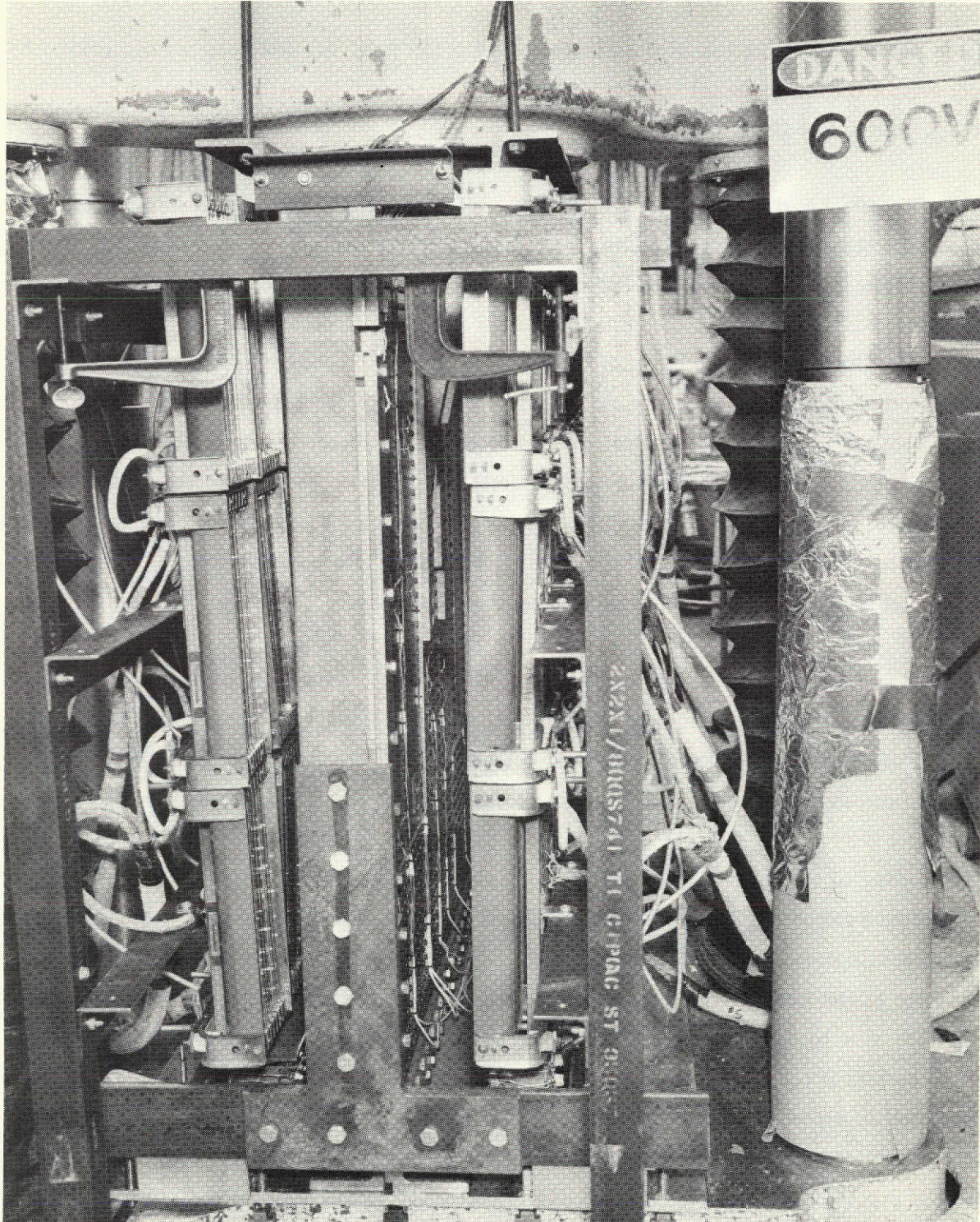Fig. 2.5-3 Uniform Load Subpanel SKJ 201004 After Testing

Fig. 2.5-4 Concentrated Load Subpanel SKJ 201007 in Test Fixture Prior to Elevated Temperature Testing

failed panel. Correlation of these results with the analysis leads to a prediction of success in the large panel test at NASA/MSFC with a failure prediction on the order of 170 percent of limit load.

Concentrated Load Subpanel, SKJ 201007. Testing of this panel was completed during 10 and 19 May using the facilities, equipment, and personnel used for the testing of the uniform load subpanel described previously. Details of instrumentation, readout, and setup were similar to the previous test. The instrumentation and side supports were installed in accordance with Drawing SKJ 201007, Appendix U. The panel was subjected to the same series of room temperature and elevated temperature tests per EM B1-M2-6, Appendix I, as was the uniform load subpanel. A modification to the heater arrays included the addition of a separate array to heat the area of the concentrated load fitting separately because of its greater mass. The test setup was similar to that shown in Fig. 2.5-1 and the detail panel arrangement is shown in Fig. 2.5-4. All of the prescribed tests were completed satisfactorily with panel failure occuring at 1,227,650 N (276,000 lb) (151 percent limit load). Figures 2.5-5 and 2.5-6 show the test specimen after testing. Two effects very evident here, as in the prior test are, (1) a marked evidence of plastic action in the sheet and stiffeners, and (2) failure cracks are not drawn to the attachments (stress raisers in any location. A complete evaluation of the test is presented in EM B1-M5-1 (Appendix T).

The testing of this panel involved an anomaly which may have affected the ultimate value of loading reached by the subpanel to some degree. Throughout the 50 and 100 percent limit load tests at both ambient and 316°C $(600^{\circ}$F) temperature, the strain gages on one side of the centerline of symmetry showed consistently higher readings than the opposite side by approximately 11-20 percent. Complete examination of the test setup disclosed no irregularities or structural anomalies. At 140 percent limit loading, an appreciable amount of yielding and load redistribution was occurring; however, the same discrepancy in readings persisted, though the magnitude was reduced to approximately 5 percent with less scatter. Correlation of these results with the analysis leads to a prediction of success in the large panel test at NASA/MSFC with a failure prediction on the order of 150 percent of limit load.
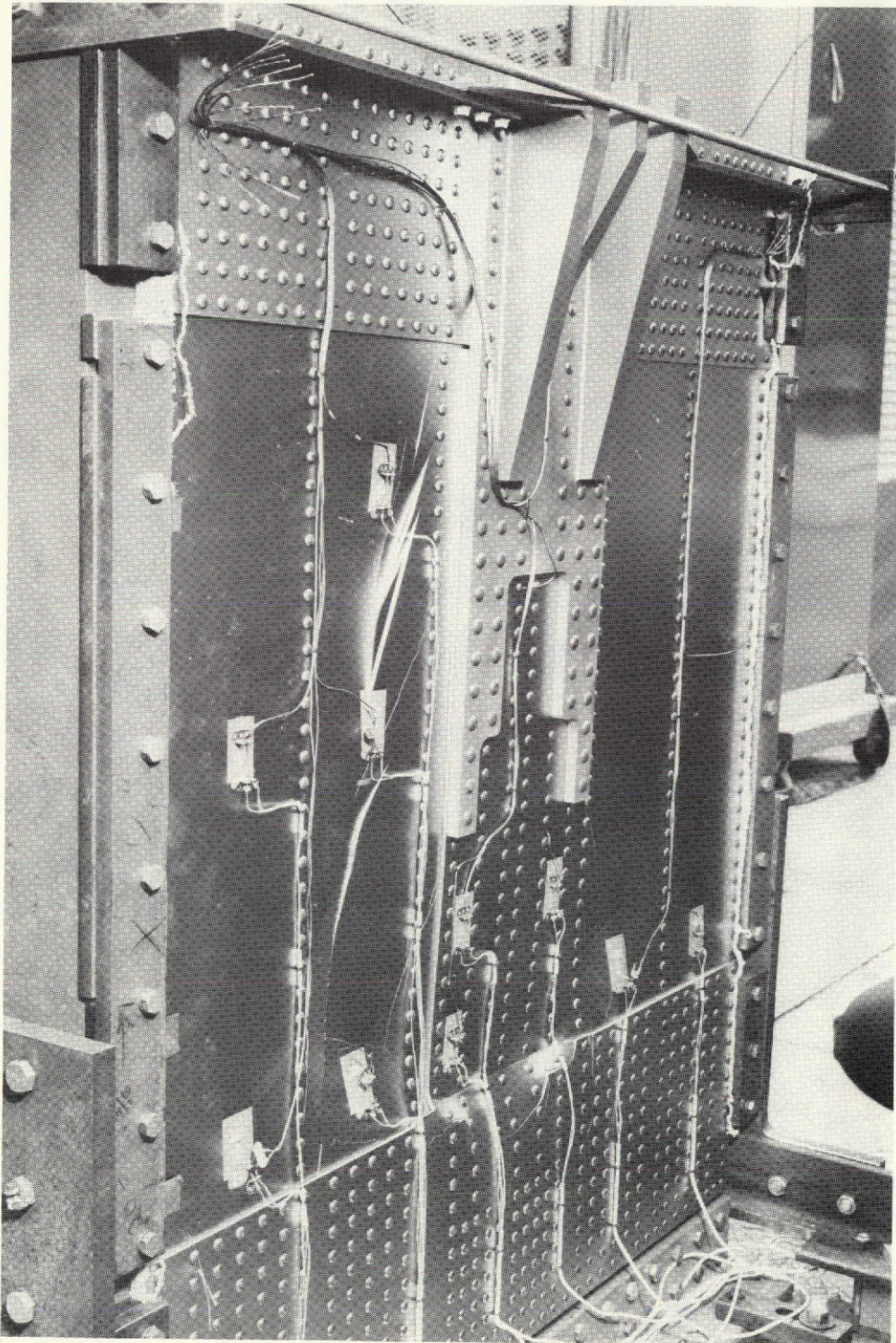
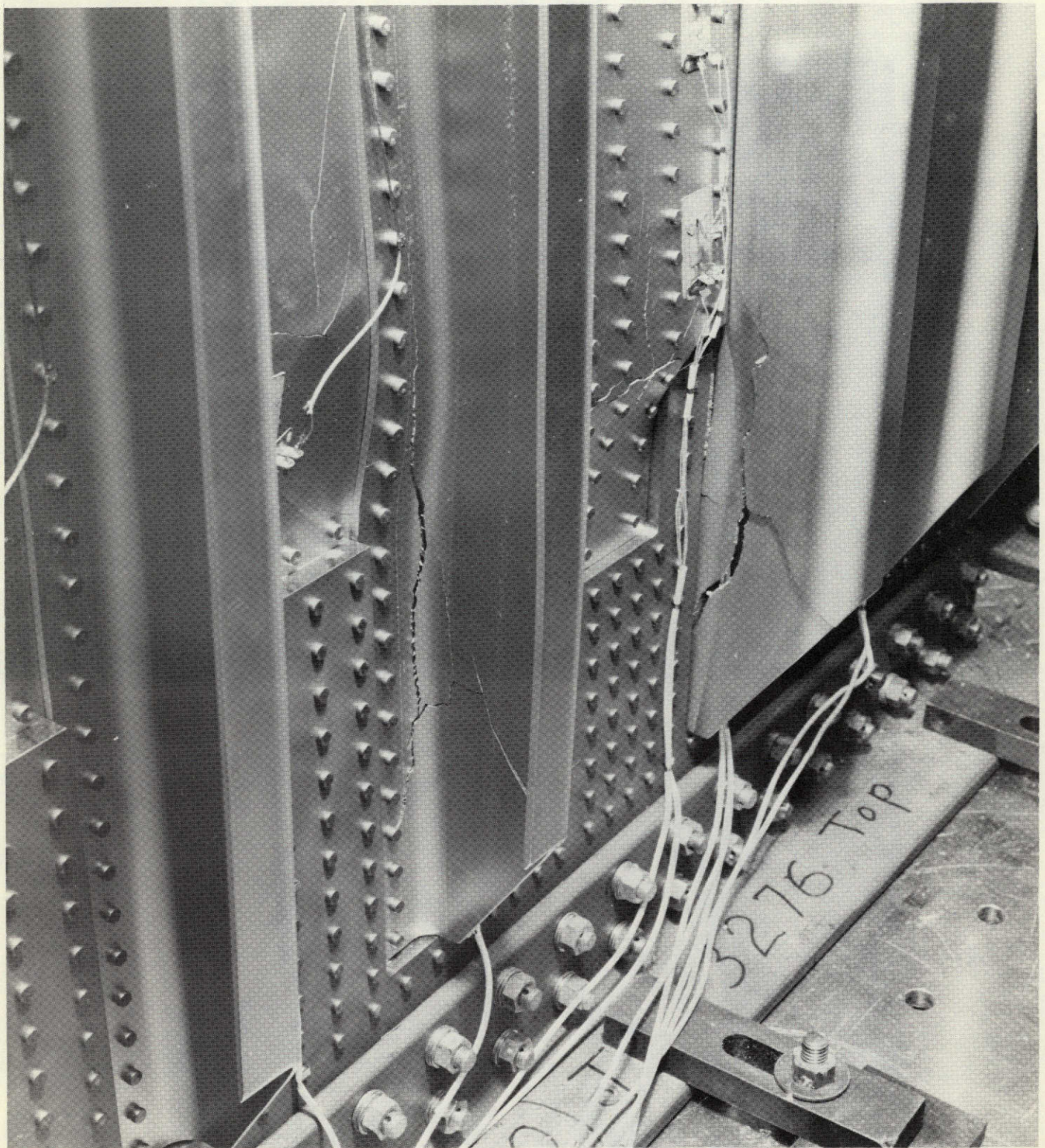Fig. 2.5-5 Concentrated Load Panel SKJ 201007 After Testing

Fig. 2.5-6 Failure Characteristics of Concentrated Load Panel — SKJ 201007

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Truss Component Testing. The test requirements for this component are defined in EM B1-M2-6 (App. I). The primary objective of this test is to demonstrate the validity of an alternate technique of construction for the truss, brazing, and the successful application of the brazing parameters developed in Phase III.

The brazed box beam assembly was tested as a cantilever beam being fixed at one end. A point load was applied at 106 cm (40 in.) distance from the fixed support. An aluminum extension arm was rigidly attached to the beryllium beam as shown in Fig. 2.3-17. A hand-operated hydraulic system controlled the applied down load which was measured with an Ormond load cell. The test setup is shown in Fig. 2.5-7.

Data of two types were recorded — X-Y plots and tabulated strain values for the deflectometers and strain gages noted in Fig. 2.3-17. A step loading was planned to progress in incremental steps from 40 percent limit load to ultimate. As loading progressed, the beam failed suddenly and catastrophically at 3610N (814 lb) about 56 percent of the design limit of 6494N (1460 lb). Post-test examination of the specimen showed a crack which travelled from one of the two alignment holes just beyond the doubler plate where the aluminum extension was attached, down through the outside member to the bottom channel at a point about 25 cm (10 in.) away towards the fixed end (see Figs. 2.5-8, -9, and -10). Primary stress at the alignment hole at failure was calcu-lated to be on the order of 69 N/mm^2 (10 ksi). Examination of the digital data after the test was inconclusive as to the cause of failure but did show the following:

- The strain gage readings were well within the plastic regime of the material.
- Back-to-back readings on one side of the compression region of the beams indicated appreciably higher strains in this location on the side plate than in the channels. All inside readings on the channels were consistent. Divergence seems to have started at a point above 40 percent limit load.
- Deflectometer readings were as expected, with some hysterisis effects from the rotation against friction in the mechanically attached end.

The early failure plus examination of the data caused suspicion in two areas — (1) incomplete brazing leading to an irregular load distribution or local effects, and (2) a material fault in the material or braze region. This led to the following company-funded effort.

Metallographic Evaluation. Following testing, the beam was subjected to a metallo-graphic evaluation in an effort to determine the origin of failure. Low power stereo microscopes were used to examine the fractured surfaces and identify suspect initiation sites which were then more closely examined using a scanning electron microscope. The results of this examination indicated failure initiated in the three-layer portion of the beam where a beryllium locating pin was brazed in place (see Fig. 2.5-8). A low power photograph of the fractured surfaces in this area is shown in Fig. 2.5-11. Fracture initiation sites are identified. It may be seen that five of the six initiation sites shown are in close proximity to the beryllium locating pin. The initiation sites are not all in the same plane, however. Sites 2 and 5 are closest to the viewer, whereas site 1 is furthest away. A low power scanning electron micro-graph, Fig. 2.5-12, shows three of the initiation sites. Striations on the beryllium surfaces can be seen pointing to these sites.

Metallographic specimens were then taken from the above area and prepared for examination. Additional specimens were taken remote from the failure origin for comparison. The microstructure of the joints at various locations was quite similar and consisted of a fine mottled braze alloy matrix in the center of the joint with evidence of intermetallic formation at the beryllium/braze alloy interfaces. The thickness of the intermetallic on each side of the joint was about 10 to 20 percent of the joint thickness. Some porosity in the joints was noted.

The photomicrograph, Fig. 2.5-13, shows an area just below the fractured surface at one of the initiation points (point No. 5 in Fig. 2.5-11). Metallographic polishing removed only a minimum of material. The beryllium pin is on the right side of the figure with a portion of the center beryllium sheet shown on the left side. Part of the U-channel section formerly occuppied the lower left portion of the figure but was torn away during failure. The uniform intermetallic (white) along the edge of the joint indicates that the U-channel section was brazed to the center beryllium sheet, but not to the locating pin. Excellent wetting and flow of the braze alloy is evidenced by the joint between the center sheet and the pin. No braze alloy was preplaced indicating that it flowed in by capillary action. A large shrinkage void is also shown at the

intersection of the U-channel, center sheet and pin. Successive polishing revealed that this void extended for a considerable distance around the locating pin and might possibly have acted as a stress-riser.

No evidence of machining damage in the beryllium was found either at the point of fracture initiation or in other locations in the beam.

In conclusion, failure analysis has located the point of fracture initiation, however, the reason for failure is as yet undefined. Further inhouse work is planned to clarify the situation in regard to the braze application in this type of structure.

2.5.2 NASA/MSFC Testing

The requirements for testing the deliverable full-scale panels were developed and modified, based on the experience derived in LMSC testing. These requirements defining instrumentation, heating and loading rates, test sequence, etc., were documented in EM B1-M2-7A (Appendix J). This section presents the results and evaluation of the testing on the two deliverable panels.

Uniform Load Panel SKJ 201002. Test will be conducted November 1972 or later and results reported.

Concentrated Load Panel SKC 201001. Test will be conducted November 1972 or later and results reported.

Conclusions and Recommendations. The subpanel tests, in general, were satisfactory and met all the test objectives. Similar test setups on the NASA/MSFC panels conducted with similar loading requirements should result in equally satisfactory results. However, there are two areas, based on this testing experience, where extra precautions are in order. The first is in the area of the heaters where difficulties were encountered in achieving a uniform temperature distribution. If similar heating devices are employed, adequate number of separate controls for the heater panels plus long soak times are recommended. The second area where extra precautions are justified is in achieving uniform loading. Utmost care in the installation of the test specimen in the test apparatus is necessary with regards to proper alignment, perpendicularity, and centering of the loading heads.
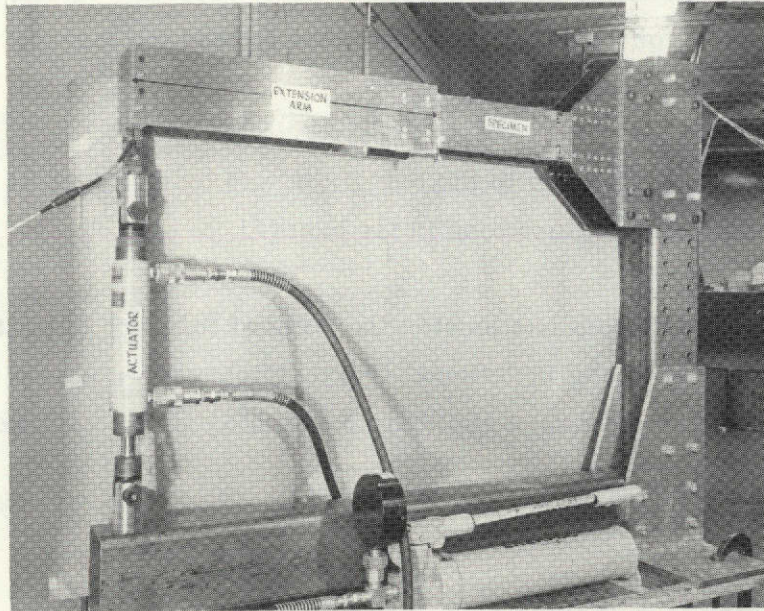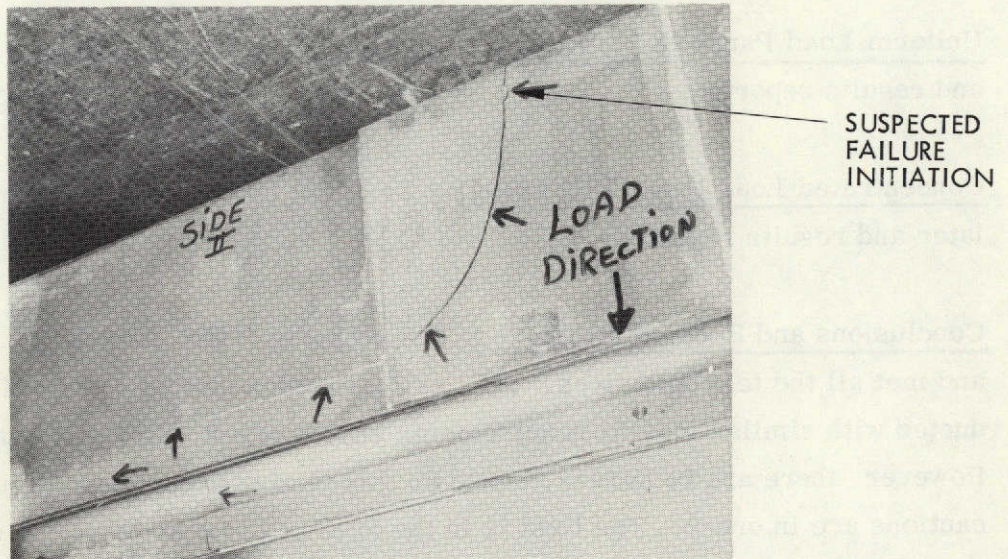
Fig. 2.5-7 Brazed Beam Test Setup

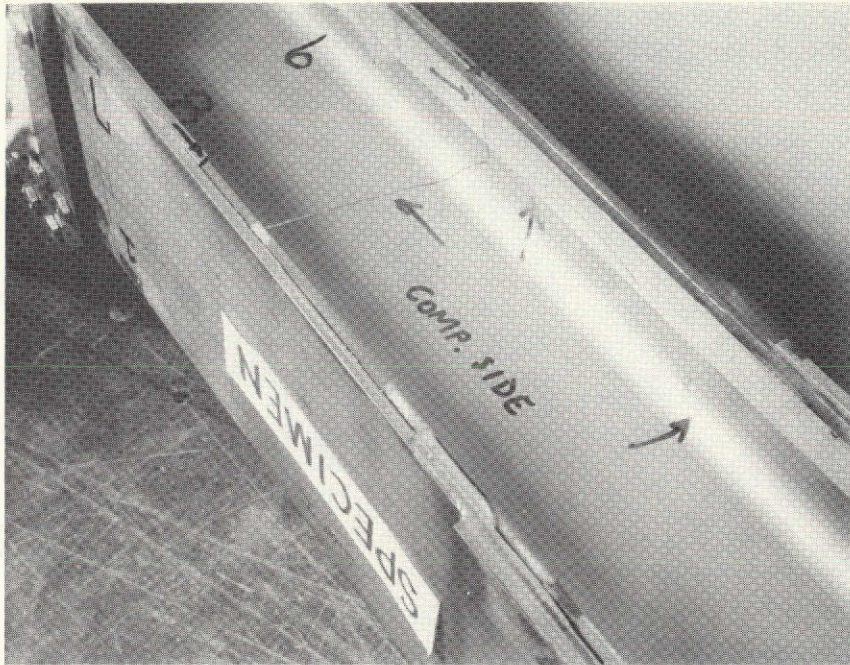Fig. 2.5-8 Brazed Beam Failure — Fixed End on Left
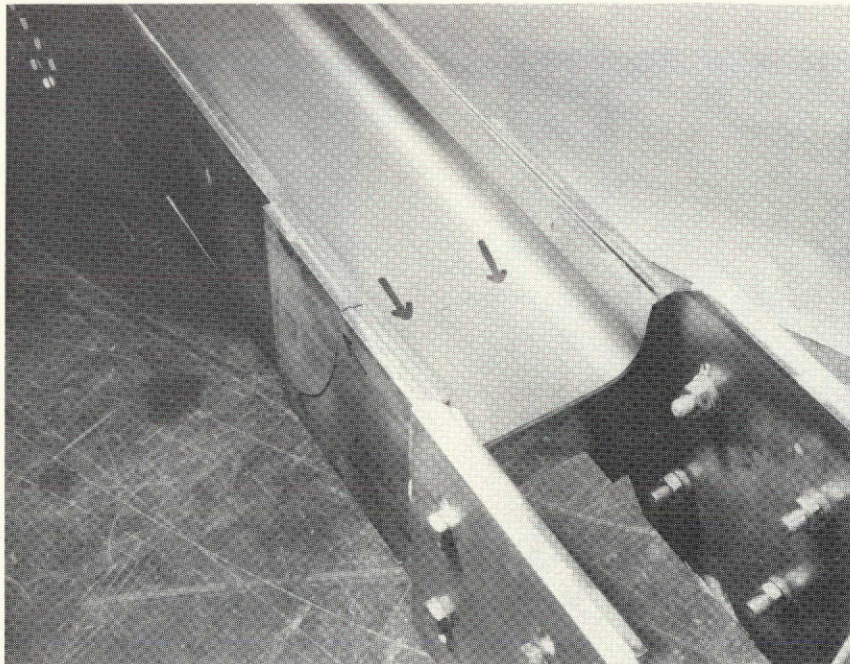
Fig. 2.5-9 Brazed Beam Failure — Fixed End on Right

Fig. 2.5-10 Brazed Beam Failure — Tension Channel Crack
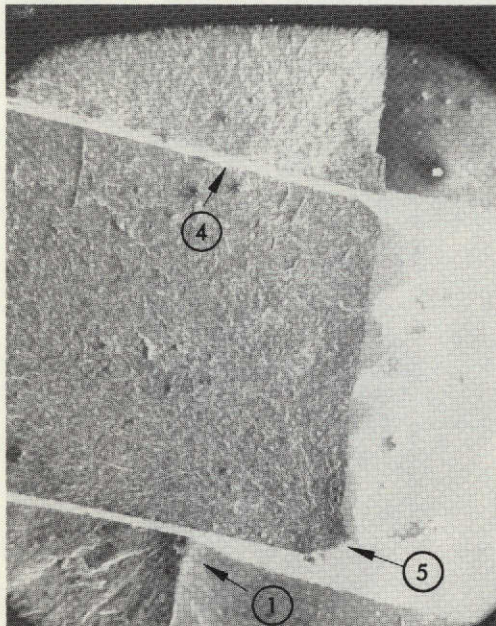
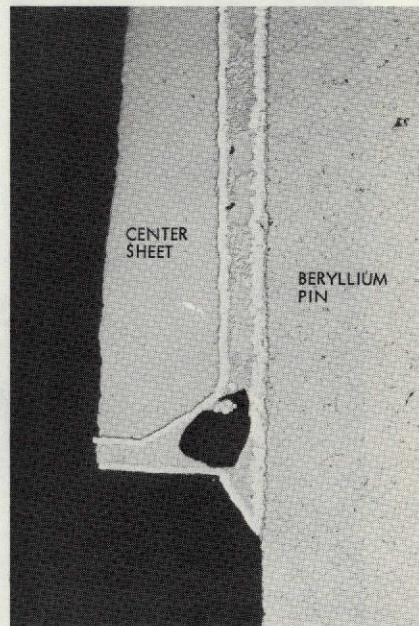**LOCKHEED MISSILES & SPACE COMPANY**
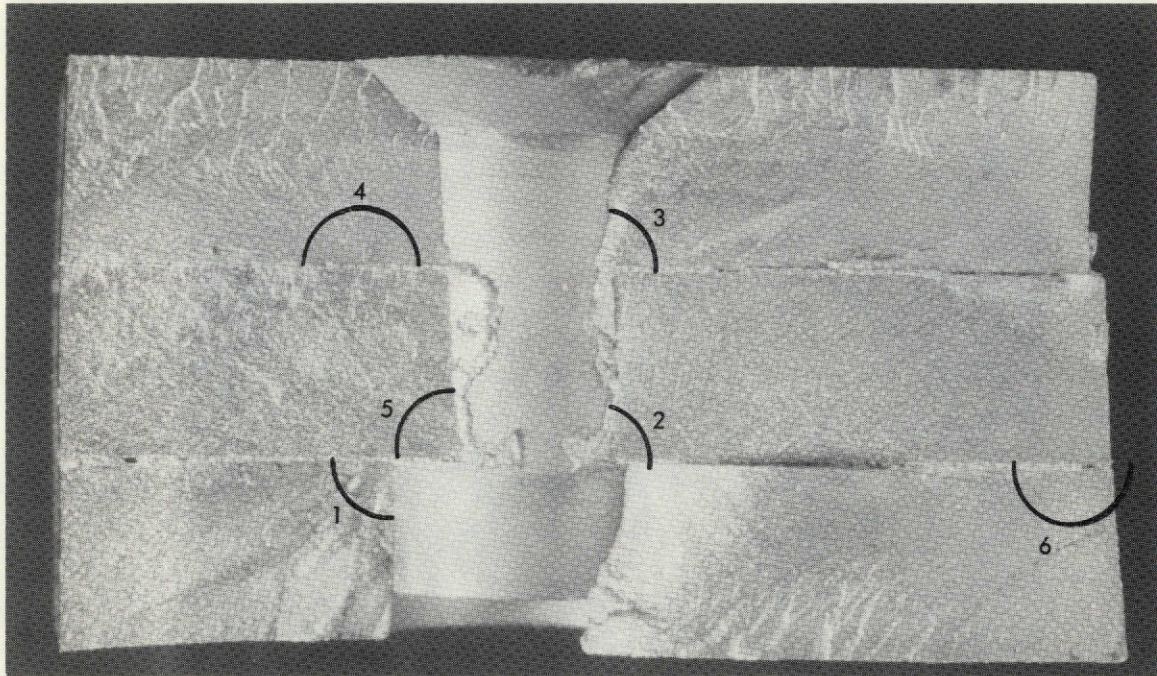
9X

Fig. 2.5-11 Fractured Surfaces at Suspected Origin of Failure.
Six Initiation Sites Are Identified.

20X

Fig. 2.5-12 Micrograph Showing
Three Fracture
Initiation Sites

100X

Fig. 2.5-13 Photomicro-
graph of Brazed
Joint At One
Failure Initiation
Site

2-100

Section 3

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

The basis for evaluating the technical feasibility of employing beryllium on Space Shuttle is its unique combination of properties. Considering only its strong points, it is an ideal material for general Space Shuttle application. Unfortunately, the initial impressions created by beryllium's weakness have not been overcome by recent improvements in fracture toughness, elongation, and cost. Generally these improvements have occurred inconspiciously, largely because of the efforts of the producers and a few interested industrial concerns. Even with its shortcomings, beryllium offers such significant potential system benefits (see Refs. 3 and 4) that it is difficult to understand the lack of emphasis on the basic material or its alloys. Beryllium has a big advantage over other advanced materials — its shortcomings are generally recognized and, with proper care, can be managed. In addition, it is relatively advanced in terms of material characterization, consistent quality, quality assurance measures, and design application. Sufficient experience now exists to indicate that (a) beryllium structures can be designed and analyzed with refined conventional techniques; (2) the basic material quality can be assured; and (3) beryllium is manageable in production.

The following paragraphs summarize the significant conclusions reached on the basis of program experience.

3.1 WEIGHT

The theoretical weight advantage of beryllium is well documented and is verified by trades in this program to be as much or more than 50 percent over that of aluminum. An important aspect of this program demonstrated that this advantage can be realized in hardware design in a predictable manner and with confidence. The panels designed and analyzed in accordance with contract requirements showed a remarkably small

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variance from preliminary design to actual hardware, considering changes in require-
ments and concept and expedient measures to achieve the objectives of the program
in an economical timely manner.

3.2 COST

Unless cost studies are conducted in depth on structures designed in detail to identical
conditions and requirements, deriving meaningful comparative costs is a challenge.
Past studies at Lockheed have shown that material characteristics, environmental
conditions, and structural concepts are such significant influences on weight that the
use of Cost Estimating Relationships (CERs), costs per pound or complexity factors,
can be inaccurate in reference to use of a candidate material on a specific structural
component. Examination of costs conducted in this program considered this aspect and
attempted to be conservative in estimates and basic assumptions. Using program-
derived information, the cost per pound of beryllium structures was shown to be less
than published information which, in LMSC's experience, can be heavily biased by the
developer. As compared to conventional aluminum structure costs, a cost factor of
2.56 was developed in the fabrication phase based on a cost of $307/lb, including
material costs. Depending on the component location on the Space Shuttle vehicle,
this can be compared to a weight cost sensitivity of $1900 to $23,400/lb, indicating
that the use of beryllium is indeed cost effective, even with the addition of DDT&E and
operational costs.

3.3 RISK

A vital element to consider is the quantification of risk. This is essential, for
although a candidate material may be light and/or result in a lower total program cost
[i.e., a more favorable Measure of Effectiveness (MOE) value], it may be engendering
a higher program risk. While risk may occur in any of the four fundamental parameters
which enter into the general system MOE (performance, reliability, cost, and schedule),
the LMSC-recommended treatment is to reflect most of these as "cost uncertainties."
Thus, if schedule is in greater jeopardy with a new candidate, as compared with a
baseline system, more development monies and "cost uncertainty" are estimated to attain
the specified schedule.

The quantification of risk is clearly beyond the scope of this program; however, the evaluation of material properties, design characteristics, and available fabrication processes indicates a relatively low risk for the design and implementation of beryllium structures similar to those on this program.

3.4 SIGNIFICANT FINDINGS

There exists within Lockheed and the rest of the aerospace industry a significant data base for the application of beryllium to aircraft, spacecraft, and missile-type structures. A number of program examples such as Agena, Polaris/Poseidon, many Lockheed spacecraft, an F-4 rudder, and others have produced an enviable record of reliability and structural performance. This data base and the results of this program provide background and confidence for use of beryllium in Space Shuttle. Some of the encouraging features defined by the program activities are:

- As-received material has excellent surface finish and thickness consistency

- There is no problem of sheet material availability, sheet sizes are adequate and being increased, and delivery is reasonable. The use of extrusions must be evaluated in terms of cost and schedule since each new size and shape is a development program within itself.

- Evaluation of material properties resulted in data generally consistent with previously derived data. Especially noteworthy were a slightly greater degradation of F_{cy} at higher temperatures, consistently high elongations, and strength properties slightly lower than MIL HDBK 5 when data are statistically analyzed.

- Workability of the material in gages used was consistent with or better than past experience. Forming of long shapes can be accomplished with correct procedures.

- Beryllium operates in most compression or stability applications to a very high percentage of its basic strength. Ring or frame spacings are large because of beryllium's high stiffness.

- Beryllium structures can be efficiently designed for high concentrated loads.

- Large numbers of mechanical fasteners can be used in complex structures with reasonable care. No rejections occurred because of the operations of drilling or rivet squeezing. Approximately 1900 fasteners were installed in each panel.

- A significant amount of redistribution takes place in multiple-fastener areas and within structures.

- Moderately high temperatures can be accommodated easily. A high percentage of its room temperature properties are available at 316°C (600°F).

- Beryllium will yield significantly before failure. Both subpanel tests recorded yield well before failure.

All of the foregoing provides confidence that beryllium should be given stronger consideration in the future. Large sizes and relatively complex structures can be accomplished.

3.5 RECOMMENDATIONS

This program, as conceived, has answered many of the fundamental questions concerning the feasibility of beryllium usage on Space Shuttle for high load applications at temperatures up to 260-316°C (500-600°F), resulting in reasonably heavy gages of material. There are extensions to this program that could enhance its usefulness for specific applications or as a general decision process for the benefit of the entire Space Shuttle program. These options should be evaluated for possible future activity in the beryllium field.

Materials. A comprehensive evaluation of mechanical properties for beryllium sheet shear and bearing strengths is needed for mechanical fastener applications. A definition of the influence, if any, of forming factors (thermal exposure, imposed strains) on residual mechanical properties is also needed.

Processes. Brazing appears to be a feasible, reliable process, but it needs more development to fully understand its applications and restrictions. Attachment tolerances can apparently be relaxed as a result of program effort; however, a more comprehensive effort is needed to allow relaxation of match drilling for cost reduction.

An evaluation of the material frangibility versus gage is desirable. Lockheed's experience is that thin sheets 0.381 to 0.625 mm (0.015 to 0.025 in.) are considerably more critical in this aspect that the gages used in this program 2.54 to 3.81 mm (0.100 to 0.150 in.).

<u>Field Repair.</u> Although the potential for damage is much less in the thicker material gages required for the construction of the specified structures, the possibility of field repair for accidental damage (because of beryllium's superior resistance to fatigue), should be examined. Alternate techniques of replacement of components, patches, and rework on location should be examined to provide an insight into the most efficient means of handling this problem area. The probability of accidental damage increases with a decrease in design loading for an efficiently-designed structure because the brittleness effects are more significant on thin gages of material. This aspect of beryllium may assume major importance if it is used in lightly loaded structures such as movable aero-surface structures, TPS structures, and low-load airframe structures. The problem of field repair may require somewhat sophisticated techniques in areas where sections cannot be replaced easily and would warrant a methodical development approach to obtain logical solutions.

<u>Extension of Temperature Limitations.</u> There are structural applications of beryllium where the ability to operate repeatedly to a temperature of $538^{o}C$ ($1000^{o}F$) may be extremely useful. It appears, therefore, that the possibility of use on items such as movable aero-surfaces, doors, and heat shielding would promote the extension of the planned materials evaluation program to encompass this regime. This would supply trends and information that could be used to initiate serious consideration of beryllium usage in components other than those presently contemplated.

<u>System Cost Effectiveness Study.</u> To properly define the appropriate structural components in which use of beryllium will be truly advantageous, a typical Space Shuttle vehicle must be evaluated in all its parts to determine the extent of risk or uncertainty associated with each prospective location, the possible benefits in terms of weight and cost-effectiveness, and the aspect of proving the technical feasibility of employing the material in an area where the design challenge is typical of most structural applications.

Because the amount of effort to reduce the risk and uncertainty varies with each application, the effort must be evaluated along with the potential gains to determine the

most practical applications within the time span consistent with Phase C/D definition. These categories should be assessed in terms of effort, risk, and time, to determine the available alternatives.

Candidate aluminum, titanium, and beryllium structural assemblies would be evaluated and compared in order to select those beryllium structures subject to subsequent detailed design and costing. The basis for this comparison and selection would be the impact on system cost and weight. Weight/cost interaction for structural candidates would be determined in relation to the current system being considered. System weight impact resulting from structural weight changes would be determined by the use of system weight sensitivity partials which relate vehicle weight change to changes in other components of the system and total system weight. This would be supported by any additional system weight estimates as required. Candidate designs would be selected by evaluation against each of two principal criteria – maximum system weight reduction and maximum space shuttle program cost reduction.

REFERENCES

1. Lockheed Missiles & Space Company, "Econometric Model for Evaluation of Advanced Materials in a Space Shuttle," Technical Proposal, Vol I, LMSC-A980347, 9 Nov 1970

2. Bellcom, Inc., "Beryllium Technology," Technical Memorandum TM-71, 1013-2, 9 Feb 1971

3. Harvey, T. J., and A. E. Trapp, "Application of Beryllium to Orbiter Primary Structure," NASA Space Shuttle Technology Conference, Huntington, Va., Mar 2-4 1970, Technical Memorandum NAS TM-X-2273, Vol II

4. Lockheed Missiles & Space Company, "Study of Materials Selection for Space Shuttle Orbiter, Structures, and TPS, Engineering Memorandum L2-01-01-M2-1, 7 Aug 1970, Rev 20 Oct 1970

5. Lockheed Missiles & Space Company, "Space Shuttle Beryllium Applications Program," LMSC-A984552, 29 Mar 1970

6. Crawford, R. F., and A. B. Burns, "Strength, Efficiency, and Design Data for Beryllium Structures," ASD TR 61-692, Lockheed Missiles & Space Company for Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Feb 1962

7. Emro, D. H., and L. Spunt, "Wing Box Optimization Under Combined Shear and Bending," J. Aircraft, Mar — Apr 1966, p. 130

8. Kuhn, Paul, J. R. Peterson, and L. Ross Levin, "A Summary of Diagonal Tension, Part I, Methods of Analysis," NACA TN-2661, May 1952

9. Fenn, R. W., Jr., D. D. Crooks, W. C. Kinder, and B. M. Lempriere, "Test Methods for Mechanical Properties of Anisotropic Materials (Beryllium Strut)," AFML-TR-67-212, Oct 1967

10. Fenn, R. W., Jr., D. D. Crooks, and W. C. Kinder, "Test Methods for Evaluating Mechanical Properties of Anisotropic Materials (Beryllium)," AFML-TR-68-373, Feb 1969

Appendix A

EM B1-M1-1

BERYLLIUM MATERIAL
EVALUATION TEST REQUIREMENTS

ENGINEERING MEMORANDUM

TITLE: 3.6 BERYLLIUM MATERIAL EVALUATION TEST REQUIREMENTS	EM NO: B1-M1-1
	REF:
	DATE: 10/4/71
AUTHORS: E. Willner	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Define the requirements for specimen tests to develop beryllium sheet material properties in representative gages for application to program, NAS 8-27739, components. The number of lots/heats to be tested will be three (3).

RESULTS

The requirements for beryllium specimen tests are presented in this document to provide the performing laboratories with information for planning purposes. Types of tests, numbers of specimen, specimen configurations, and environments are outlined.

DISCUSSION

Although the intent is to provide beryllium sheet according to existing specifications, recent investigations at Lockheed Missiles & Space Company have revealed a significant improvement in the capacity of beryllium to absorb energy prior to fracture. Therefore, those material parameters considered necessary to examine improved ductility will be investigated, as well as the properties contained in Standard Lockheed Missiles & Space Company Beryllium Specification (LAC 07-4008A) for the procurement of sheet. These added requirements include interrelationships, not only in material chemistry, but also in mechanical properties. Three sheets from each heat shall be evaluated as described herein.

Standard Tensile Test. Tensile and yield strengths as well as elongation shall be determined at room and elevated temperature for those parameters listed in Table I.

Compression Test. Compression yield will be determined for those parameters listed in Table II.

Three-Point Bend Test. A single specimen will be selected from each sheet. Each specimen will then be tested in three-point loading at room temperature, 300°F and 600°F. A total of 18 room temperatures and 36 elevated temperature tests shall be performed.

<u>Chemical Etching</u>. Since cutting or machining produces surface damage in beryllium by twinning, the surface damage must be removed by etching to avoid premature failure under stress. All specimens will be etched a minimum of 0.002 in./side. If machining operations become severe or abusive, very low ductility and tensile strength may be avoided by using an etch of 00.005 in./side. The shoulders of specimens containing pin-holes must be etched to remove machining damage, even though the area beside the pin hole is twice that in the reduced sections if premature failures through the pin hole are to be consistently avoided.

<u>Specimen Preparation</u>. The following procedures will be used in preparation and testing of beryllium specimens.

- Etch 0.005/side

- Etch shoulders as specimens as well as reduced sections

- Reinforce holes in ends of specimens with adhesive bonded tabs when bearing strengths appear to be marginal.

- Utilize 0.001 to 0.002 in. taper from ends to center of tensile specimen reduced section to minimize failures outside gage length.

- Use pin holes for alignment of stress and specimen axes when feasible for tensile type tests.

<u>Strain Measurement</u>. Typical strain gage installations shall be calibrated against ASTM Class A when possible. When small strains are to be measured, instrumentation shall be carefully checked for drift, warmup, and line voltage to avoid problems. Full bridge and other techniques such as higher input voltage will be used to minimize reading errors. Strain deviation analysis will be used to obtain maximum accuracy from strain data.

<u>Modulus Test</u>. Specimens will be preloaded prior to installation of bonded strain gages to increase proportional limit, elastic ranges, and potential accuracy of the elastic specimen.

<u>Tensile Tests</u>. Room temperature and elevated temperature testing will be performed in accordance with those procedures recommended by ASTM 21 and as described in previously reported investigations by Lockheed Missiles & Space Company.

<u>Compression Tests</u>. Compression tests will be accomplished on 1/2 x 2 inch specimen using techniques described by R. W. Fenn, Jr. in "Evaluation of Test Variables in the Determination of Elevated Temperature Compressive Yield Strength of Magnesium Alloy Sheet, "ASTM Special Technical Publication 303, 1961 p48. Specimens will be supported by a spring-loaded stainless jig and will be compressed at a constant crosshead rate to produce a strain rate of 0.002 in./in./minute. Strain will be measured on the center one inch of the specimen

using extensometers wired to average strain from opposite sides of the specimen electrically.

Three-Point Bend Tests. Three-point bend tests will be made on the one-inch wide specimens by applying a load at the midpoint of a 2.00 span. Load will be applied through 0.375 in.-diameter dowels using a constant cross-head rate of 0.05 in./min. Deflections will be measured to the nearest 0.0001 in. -by autographically recording the relative displacement of the loading mandrels. Extrapolation of the modulus line on load-deflection curves will permit the elastic and plastic deflections to be read from these curves. Calculation of the bend angle applicable to a particular deflection will be accomplished by dividing the deflection by the half-span (1.00 in.), determining the angle whose tangent agrees with the ratio, and doubling this angle to obtain the bend angle.

Fracture Toughness Testing. Although fracture toughness of beryllium sheet has been performed , further work is required. However, within the limits of this test program, specimens will be prepared by introducing a pre-crack at room temperature at cycles not to exceed 10^0, to a depth not to exceed 1/2 thickness. It may be necessary to introduce the pre-crack at 500^0 to 900^0F in order to propagate a directionally controlled flaw. Methods of analysis will be similar to those previously used and other solutions may be applied in order to develop an apparent fracture toughness (K_{IC}). Plane strain cannot be assured in the thickness contemplated for this test program. The following two precautions must be noted:

- The sensitivity in calculating K_{IC} can vary with depth of cracked-flaw. This is a phenomenon that is recognized and cannot be modified by testing techniques or analysis.

- The pre-cracking techniques may influence K_{IC}.

Fatigue Testing. Axial tension fatigue evaluation shall be performed with a minimum to maximum stress ratio of R = .2.

Impact Testing. Standard Charpy V-Notch specimens in profile will be evaluated. Thickness of specimens will be the thickness of the beryllium sheet less the normal removal of material attributable to etching after machining. Specimens will be tested within 3 seconds of removal from the thermal environment. Specimens will be handled by means of pre-heated tongs and placed on the anvil of a Compound Pendulum Precision Impact Machine with a maximum capacity of 24 ft-lb and a resolution sensitivity to 0.005 ft-lb. Temperature changes would be monitored on selected specimens by means of a thermo-couple attached by percussion welding. Thus, a time-temperature history for each specimen will be provided. Data will be plotted showing ft-lb versus temperature and in-lbs/in^2 (net area) versus temperature.

Modulus of Elasticity. Precision modulus of elasticity shall be determined for each orientation for each lot/heat. However, orientations shall be selected at random for testing for evaluation of single specimens at room temperature.

Fracture Toughness at Room Temperature. Single specimens shall be evaluated for apparent K_{Ic} for at least one sheet and orientation for each heat. A total of at least ten specimens shall be tested at room temperature.

Fatigue Testing at Room Temperature. Testing shall be performed for at least five specimens for one sheet of two heats. A total of at least twenty specimens shall be tested at room temperature.

Impact Tests. Two specimens shall be tested for at least one sheet of two heats. Tests shall be performed at room temperature, $300^{\circ}F$ and $600^{\circ}F$. A total of at least 24 impact tests shall be made.

Creep Testing. Creep testing shall be performed at $300^{\circ}F$, $600^{\circ}F$, to consume a total time of 100 hours exposure at each temperature. Creep strain shall be determined for at least three stress levels at each temperature. This testing shall be performed on at least one sheet for one lot/heat. At least one specimen shall then be exposed to a simulated mission profile for at least five cycles to determine extent of creep.

Mission Profile. The specimen shall be exposed to a constant stress of 29,000 psi. The temperature shall rise uniformly to $600^{\circ}F$ after 180 seconds from ambient temperature.

Specimen Preparation. Specimen blanks will be prepared in the Lockheed Missiles & Space Company beryllium production machine shop. Tracer mills or lathes with carbide cutting tools will be used with the same machining techniques developed for production of the beryllium shins for the Agena spacecraft. In all cases the dust and chips created in machining, grinding, or polishing operations will be picked up by high-velocity exhaust systems to avoid contamination of the area with toxic beryllium particles. Slots for fracture toughness specimens or pin holes for the ends of specimens will be machined by electric-discharge machining techniques.

Test Specimen Geometry. Geometry and dimensions for the sheet test specimens are shown in Fig. 1. Shoulder radii of 1/2 in. for longitudinal and transverse sheet tensile specimens shall be used. An edge/hole diameter ratio (e/D) of 1.5 for the longitudinal and transverse tensile specimens and 2.0 for the modulus specimens will be used. The modulus specimen shown is a simple specimen to make for elastic measurements but is not satisfactory for yield or tensile strength studies because it will fail in tension through the holes.

<u>Creep Testing Control</u>. There will be periodic monitoring of temperature for drift limited to 3°F. Temperature will be controlled within $1\frac{1}{2}^{\circ}$F. Continuous strain versus time information will be obtained.

<u>Metallurgical Examination</u>. Optical metallographic techniques shall be used to examine the grain structure of selected sheets of beryllium.

Table I

TENSILE TESTING PARAMETERS

Number of Specimens for Test

Lot/Heat	Sheet	R.T.		300°F		600°F	
		L	T	L	T	L	T
I	a	3	3	3	–	–	3
I	b	3	3	–	3	3	–
I	c	3	3	–	3	–	3
II	a	3	3	3	–	3	–
II	b	3	3	–	3	–	3
II	c	3	3	–	3	–	3
III	a	3	3	3	–	3	–
III	b	3	3	–	3	–	3
III	c	3	3	3	3	3	–
	TOTAL	27	27	12	18	12	15

Total Specimens – 54 – ET
                  57 – RT
     TOTAL   111

Table II

COMPRESSION TEST PARAMETERS

Number of Specimens for Test

Lot/Heat	Sheet	R.T.		300°F		600°F	
		L	T	L	T	L	T
I	a	3	3	3	-	3	-
I	b	3	3	-	3	-	3
I	c	3	3	-	-	-	-
II	a	3	3	3	-	-	3
II	b	3	3	3	-	3	-
II	c	3	3	-	3	-	3
III	a	3	3	-	3	3	-
III	b	3	3	3	-	-	-
III	c	3	3	3	-	3	-
TOTAL		27	27	15	9	12	9

Total Specimens - 45 - ET
                  54 - RT
        TOTAL   99
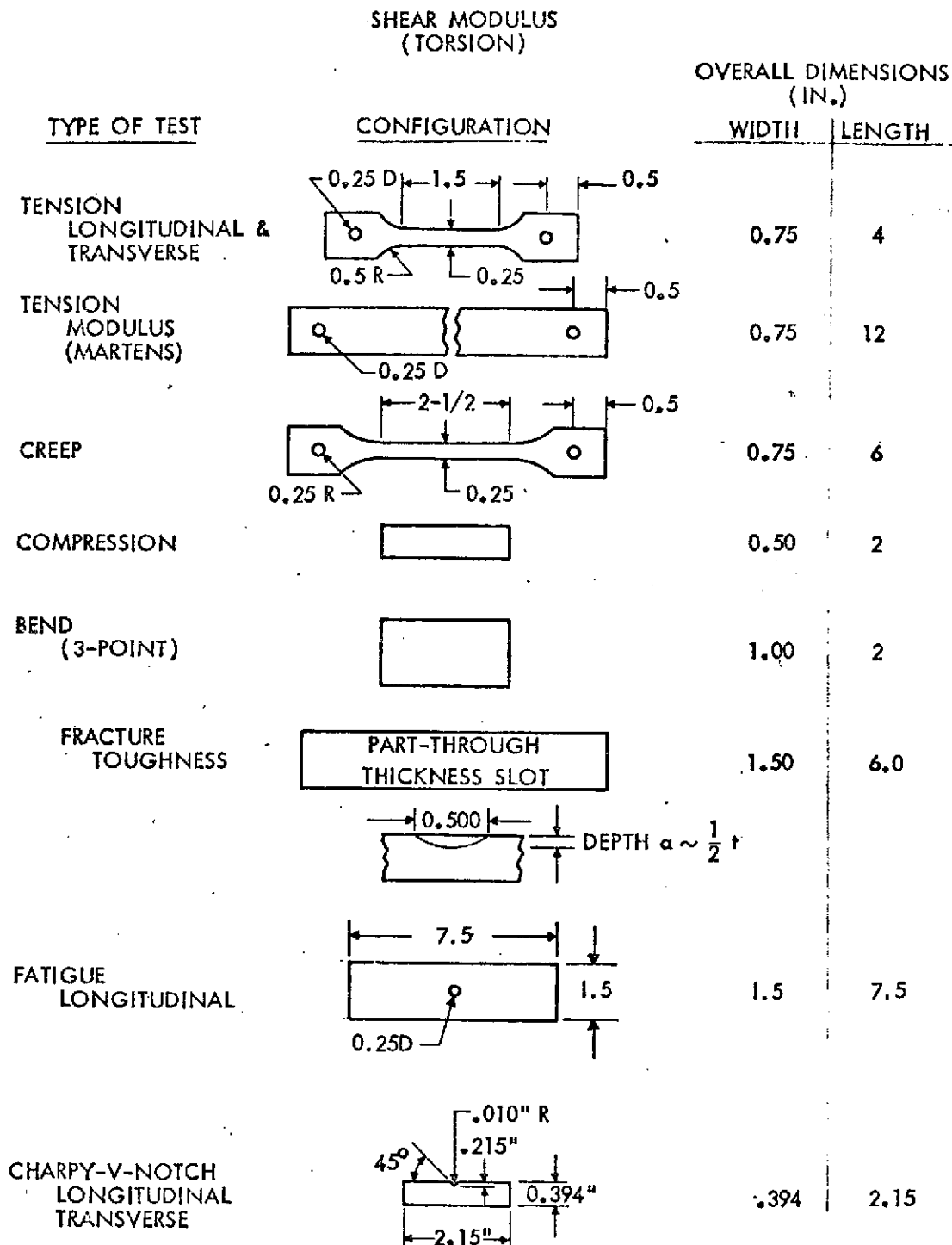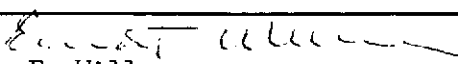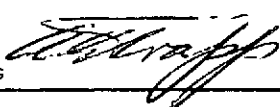
Fig. 1 — Test Specimen Geometries

Appendix B

EM B1-M1-2A

TEST SPECIMEN CONFIGURATION
AND IDENTIFICATION

ENGINEERING MEMORANDUM

TITLE: Test Specimen Configuration and Identification	EM NO: B1-M1-2A
	REF: 31 July 1972
	DATE: 21 December 1971
AUTHORS: *[signature]* E. Willner	APPROVAL: *[signature]* ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Provide detail configuration requirements for the manufacture of test specimen coupons for evaluation of material properties described in EM B1-M1-1 per NAS 8-27739.

RESULTS

Detail sketches are presented herein for specimen coupon requirements. Codification is developed and presented herein for identification of a given specimen for a given test.

DISCUSSION

Processing details for the manufacture of test coupons are described in B1-M1-1.

Codification. Table I describes the code used in identifying each specimen for each test.

Figure 1   Details for Beryllium Compression Specimen
Figure 2   Details for Beryllium Creep Specimen
Figure 3   Details for Beryllium Tension Modulus Specimum
Figure 4   Details for Beryllium Sheet Fatigue Specimen
Figure 5   Details for Beryllium Tensile Specimen
Figure 6   Details for Beryllium Sheet Charpy Specimen
Figure 7   Details for Beryllium Sheet Bend Specimen
Figure 8   Details for Beryllium Part Through Thickness Specimen

CODE
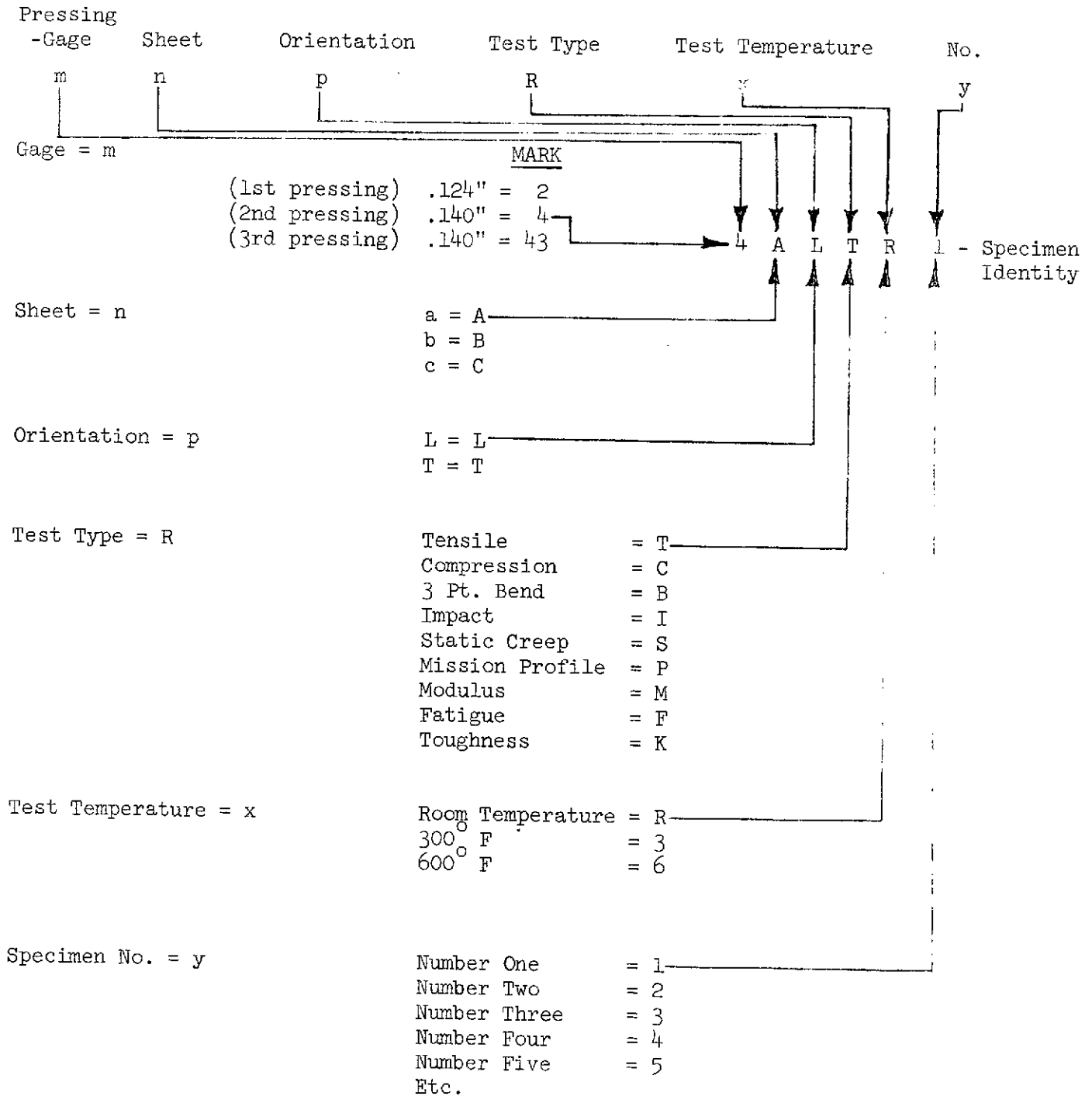
Pressing -Gage	Sheet	Orientation	Test Type	Test Temperature	No.
m	n	p	R	x	y

Gage = m

MARK

(1st pressing) .124" = 2
(2nd pressing) .140" = 4
(3rd pressing) .140" = 43

4 A L T R 1 - Specimen Identity

Sheet = n

a = A
b = B
c = C

Orientation = p

L = L
T = T

Test Type = R

Tensile	= T
Compression	= C
3 Pt. Bend	= B
Impact	= I
Static Creep	= S
Mission Profile	= P
Modulus	= M
Fatigue	= F
Toughness	= K

Test Temperature = x

Room Temperature	= R
300° F	= 3
600° F	= 6

Specimen No. = y

Number One	= 1
Number Two	= 2
Number Three	= 3
Number Four	= 4
Number Five	= 5
Etc.	

32/ ALL SURFACES

/3\

X

2.000

.500

STOCK THICKNESS

MAX. TAPER .002 /1\
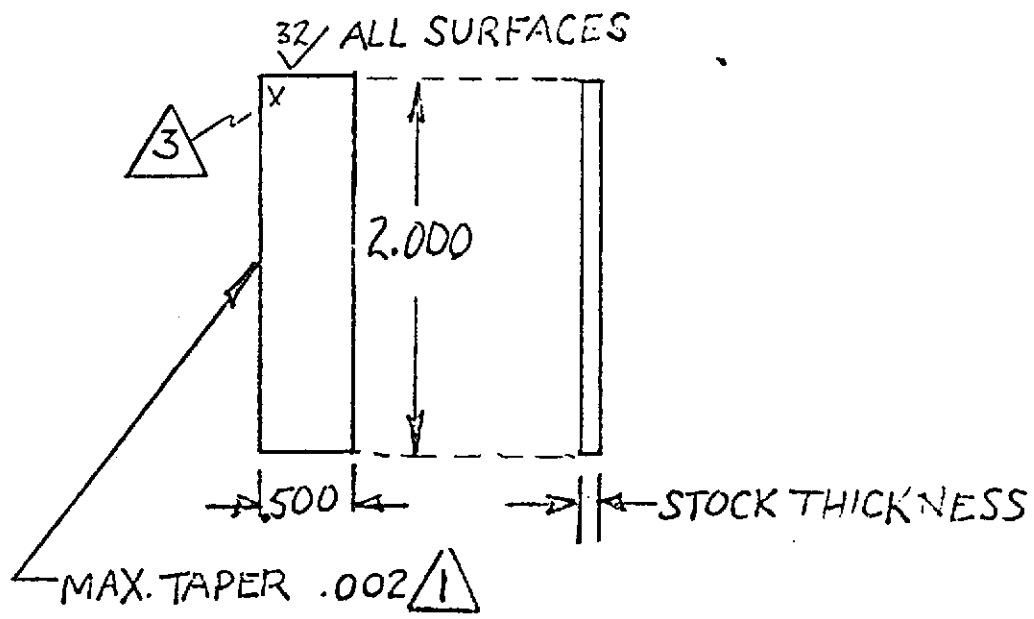
SCALE 1.0" = 1.0"

/3\ LIGHT IDENTIFICATION THIS AREA ONLY.
DO NOT MAR END SURFACES.

2 TOLERANCE ±.010 EXCEPT AS NOTED.

/1\ ALL SURFACES MUST BE FLAT, SQUARE,
AND PARALLEL.

NOTE:

FIGURE 1

WIDTH .406" ±.005
SYMMERTICAL ABOUT ⊥ ±.001"

5/16" RAD.
DO NOT UNDERCUT

.025 DIA. HOLE
& CHAMFER

MIN.
.377 DIA. HOL
AFTER ETCH

HOLE ON
⊥ ±.001"

.406 ±.005

17/32"

1 1/16"

2 1/8" FILLET
DISTANCE

2 3/4"

13/16"

1 5/8"

6"
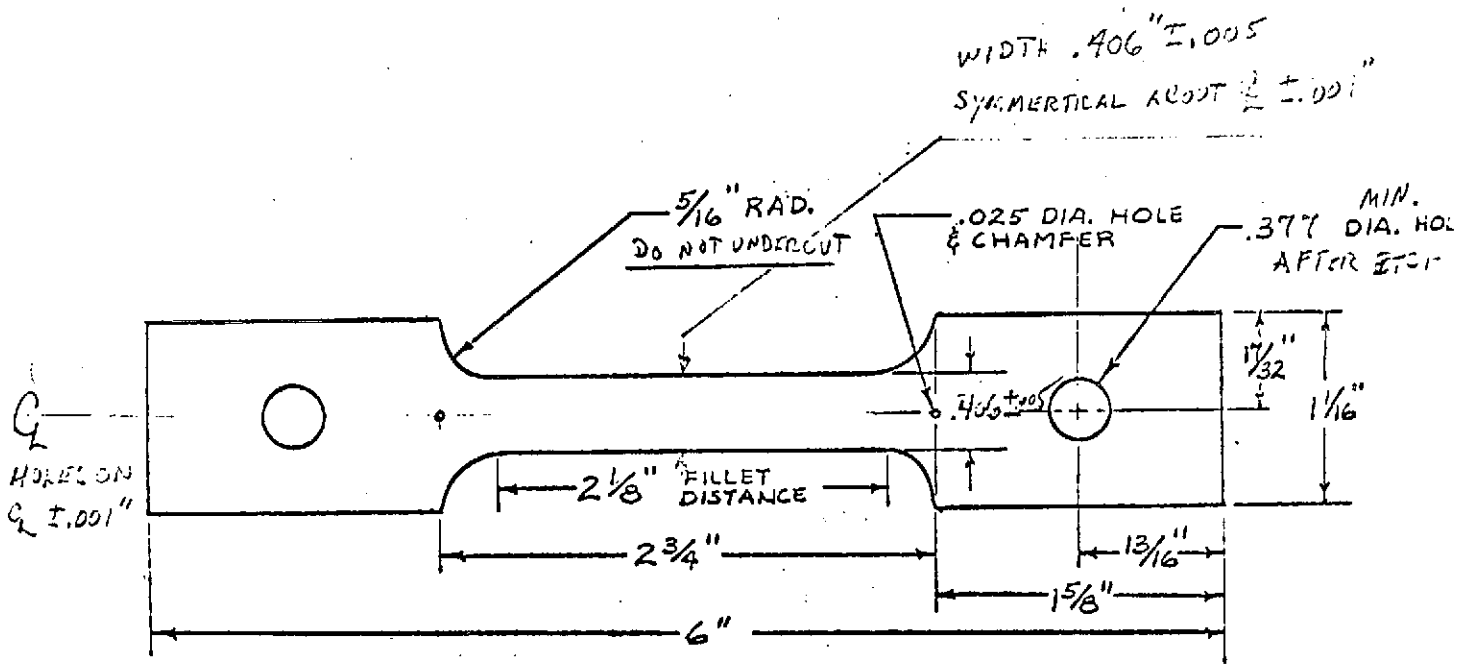
SCALE 1:1

SHEET SPECIMEN

Figure 2

B-4

Prepared	NAME D.D BROOKS	4/13/11
Checked		
Approved		

LOCKHEED AIRCRAFT CORPORATION
MISSILES and SPACE DIVISION

TITLE *TENSION MODULUS*
TUCKERMAN + STRAIN GAGE

	TEMP.	PERM.
Page		
Model		
Report No.		

0.50 R DO NOT UNDERCUT

W = .250

W +.002 +.001 (TYP.)

.050

.750

0.250 D.

2.500

6.00
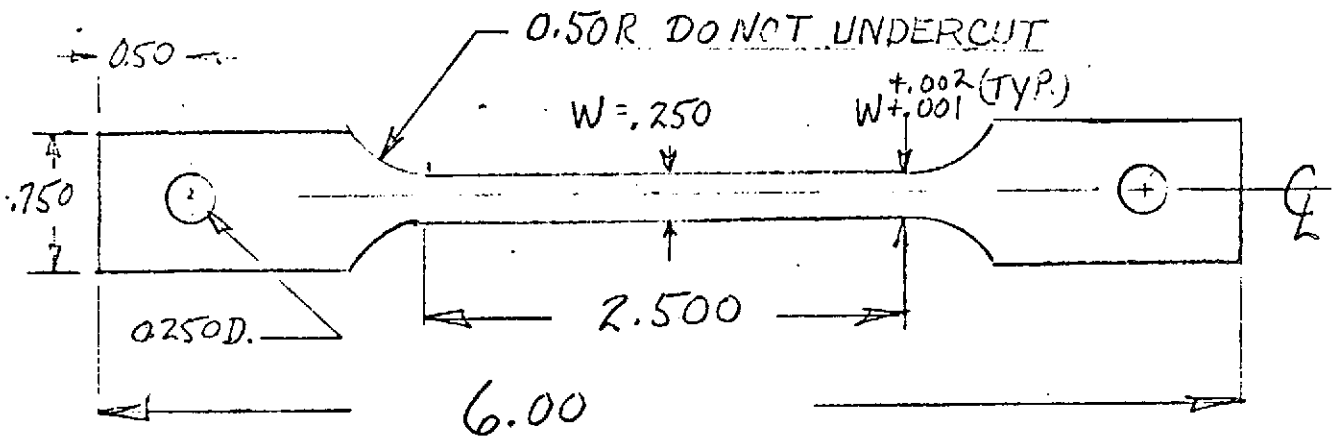
1. HOLES AND REDUCED SECTION TO BE SYMMETRICAL ABOUT THE ₵ WITHIN ± 0.001 IN.

2. LINEAR TOLERANCE ± 0.010 IN.

Figure 3

B-5

A

A/2

B

NO CHAMFER

C

C_L

TYPE A SPECIMEN
NOTCHED — K_{t_g}=3.0

	NOMINAL SPEC SIZE	A	B	C	DIMENSIONS
	1 1/2	7.50	.250 .245	1.50	INCHES

4   LINEAR TOLERANCE ±.010

3   MATERIAL THICKNESS

2   TO BE SYMMETRICAL
    ABOUT CENTERLINE
    WITHIN ±.001 IN.

1   ORIENTATION TO BE SPECIFIED

Figure 4

4.00

.50 (TYP.) — .750 — 1.500 — .750 — .50

SYM. TOLERANCE ±.001

.750 — C_L

W .250

0.5 R (TYP.) — $W^{+.002}_{+.001}$ (TYP.)

DO NOT UNDERCUT

0.255
0.250 DIA.

⚠ IDENTIFICATION MARK

2 TOLERANCE ±.010 IN. EXCEPT AS NOTED

Figure 5

B-7

$$L = 2.165 {}^{+0.000}_{-0.100}$$

$$90° ± 10'$$

SHEET THICKNESS

0.010 R ± 0.001

$0.394 ± 0.001$

$0.315 ± .001$

$22\frac{1}{2}°$

$\frac{L}{2} ± .013$

$\frac{32}{\vee}$ ALL EDGES

$4.5° ± 1°$

SCALE 1.0 IN. = 2.0 IN (APPROX.)

Figure 6

FORM LMSD 362B-1 LIETZ 1118 TOPFLIGHT

1.00

2.00

SHEET THICKNESS

SCALE 1 IN. = 1 IN.

LINEAR TOLERANCE ±.030

Figure 7

½ SHEET THICKNESS

0.500

SLOT WIDTH 0.010 ±.003
ROOT RADIUS LESS THAN 0.001

1.500

3.000

6.000

SLOT TO BE MACHINED BY EDM
TOLERANCE 0.010" EXCEPT AS NOTED
SCALE 1.0 IN. = 1.0 IN.

LOCKHEED AIRCRAFT CORPORATION
MISSILES and SPACE DIVISION

NAME D. D. Cross

DATE

Prepared

Checked

Approved

TITLE
PART THROUGH THICKNESS

Page   Model   TC-IP   PLRM
Report No.

Appendix C

EM B1-M1-3

MATERIALS EVALUATION
TEST DATA AND ANALYSIS

ENGINEERING MEMORANDUM

TITLE: MATERIAL EVALUATION TEST DATA & ANALYSIS	EM NO: B1-M1-3
	REF:
	DATE: 1 August 1972
AUTHORS: E. Willner	APPROVAL:
	ENGINEERING
	SYSTEM ENGRG

PROBLEM STATEMENT

This document reports and analyzes the test data developed in Phase I, Materials Evaluation, of the program "Evaluation of Beryllium for Space Shuttle Components," NAS 8-27739.

RESULTS

Test data has been obtained from supplied material for tensile and compression properties (RT, 300°F and 600°F), creep strengths (100 hr to 300°F and 600°F), creep strain (thermal profile from RT to 600°F, fracture toughness, modules of elasticity, fatigue, three point bending (RT, 300°F and 600°F), and Charpy V notch impact strengths (RT, 300°F and 600°F). Test and specimen requirements are based on EMs B1-M1-1 and B1-M1-2.

Tension and compression data were statistically analyzed for interpretation as Military Handbook 5 type properties. Photomicrographs were also prepared for metallographic analysis.

DISCUSSION

Test Material

Beryllium sheet used in this program was procured to meet all requirements of LMSCI Material Specification LAC-07-4008A. Kawecki-Berylco Company(KBI) furnished sheets produced from three different pressings. (For clarity, the source for a given sheet is the "pressing." The expression "heat" will have no significance herein except as parenthetically noted under "Producers Identity" in the tables of test data.)

KBI has certified the chemistry for each pressing and the analyses of each is tabulated in Table 1. The chemistry met requirements of LAC 07-4008A.

A total of 15 cross-rolled beryllium sheets were produced from the three pressings. Five sheets of 0.124-inch thickness were made from pressing 379P, four sheets of 0.140-inch thickness from pressing 395P, and six sheets of 0.140-inch thickness from pressing 432P. Sheets of the 0.124-inch gage were received 35 inches wide by 91 inches in length; the 0.140-inch sheets from pressing 432P were received 30 inches wide and 84 inches in length; the 0.140-inch sheets from from pressing 395P were received 30 inches and 84 inches in length except for

sheets H-1515 and H-1516 which were approximately 77 inches in length. Table 2
lists the KBI data for room temperature tensile properties. These properties
meet the mechanical property requirements of LAC 07-4008A. Three sheets
from each pressing were selected at random for the materials evaluation.

Tensile Tests

An outline of those tensile tests made for this program at LMSCI is presented in
Table 3. Tensile data obtained for each sheet from each pressing is shown in
Tables 4, 5, and 6. Typical tensile load strain curves are shown in Figures 1, 2
and 3. Specimens were cut to meet requirements of EM B1-M1-2.

All tensile tests for deteriming yield strength, tensile strength, and elongation
were made in a 10,000 pound capacity Instron testing machine utilizing two
Wiedmann-Baldwin lightweight type 2-M extensometers assembled as one extenso-
meter and wired electrically to average strain on opposite sides of the specimen.
Room temperature tests were conducted at a constant cross-head rate of 0.01 in./
in. to ~1% strain and 0.1 in./min. from ~1% strain to failure. ASTM extenso-
meters, class B-2 which is the classification of the T-2M extensometers used, are
not considered adequately precise for determination of Young's modulus. Conse-
quently, the load-strain curves obtained from the Instron recorder were used only
for the determination of tensile yield and ultimate strength.

The tensile properties at 300° F and 600° F were determined in accordance with
ASTM recommended test procedure E21-70 using a Marshall resistance heated
furnace controlled to ± 3° F and a Microformer extensometer, Model PSH-8MS.

Statistical Analysis of Tensile Data

Figures 4 through 13 reveal the behavior of Mil-Handbook-5 Type A and B as well
as typical values from pressing to pressing over the range of test temperatures.
Further, an interesting note of behavior is shown in Figures 14 and 15 in which
a correlation is made of tensile properties to iron and aluminum chemistry.
Results of the statistical analysis for program data are presented in Table 7 as
Military Handbook-5 Type A and B values. Good agreement is shown for the
tensile ultimate properties at room temperature; however, Tensile Yield Strength
A and B values are shown to be about 6% lower than current Military Handbook-5
minimums.

Compression Tests

The compression yield strengths conducted at LMSCI for this program are outlined in Table 8. Compression data obtained is shown in Tables 4, 5, and 6. Typical load strain curves are shown in Figure 16.

Compression tests were accomplished by techniques previously used. Specimens cut to meet EM B1-M1-2 requirements were supported by means of a spring-loaded stainless steel jig. Specimens were compressed at a constant cross-head rate of 0.01 in./min., which provided a strain rate of ~0.002 in./in./min. Strain was measured electrically on the edges of the center 1-in. of the specimen using two Wiedmemann-Baldwin Model T2-M extensometers wired to average strain from opposite sides of the specimen. Resistance heating of René 41 platens fixturing and specimen, was employed for the elevated temperature testing, control of temperature was ± 3° F.

Statistical Analysis of Compression Data

Figures 17 through 20 reveal A and B value compression behavior typical of Military Handbook-5 methods for pressing to pressing over the range of test temperatures. A correlation of compression data from iron to aluminum chemistry appears in Figure 21. This is similar to Tensile Behavior shown in Figures 14 and 15. Table 7 contains A and B values for compression yield strength.

Creep-Strain Testing

When this program began, creep-strain equipment at LMSCI had been committed to other activities. Consequently, the constant load creep-strain testing was performed by the Joliet Metallurgical Laboratories (JML), Joilet, Illinois. This test effort was performed under direction of LMSCI. The test specimen was designed to conform with JML test configuration shown in EM B1-M1-2. Specimens were prepared and etched at LMSCI, then forwarded to JML for creep testing. Averaging dial gage indicators accurate to 0.001 inch, were assembled with an extensometer prior to loading. Marshall furnaces were used for heating and were controlled to within 3° F, and the standard practice of incremental loading was used. After the load was placed, incremental strains were immediately read off the dial indicators. Periodic readings were made.

Table 9 summarizes the creep-strain data. Figure 22 is a plot of the 100-hour creep strain for the two sheets 300° F and 600° F. Strain rates were calculated, and are listed in Table 9. Because of the large scatter, no sensible strain rate plot can be presented. This scatter is considered normal for creep testing. Additional specimens would be required to develop a meaningful analysis.

Creep Strain on Thermal Cycling

One specimen was subjected to 25 cycles of thermal excursions from room tem-
perature to 600°F. The rate of rise in temperature was maintained uniformly so
that 600°F would be reached in three minutes. The specimen was loaded to a
stress of 29,000 psi. Permanent strain was measured after five cycles, followed
by two 10-cyle exposures. Total strain or permanent set was measured, in con-
trast to the plastic component measured during the 100-hour creep-strain tests.
Data for the thermally cycled specimen is shown in Table 10. Apparently, at
29,000 psi, the specimen underwent the major percentage of creep within the first
five thermal cycles. Note the addition of an apparent .003 percent strain after 15
cycles and no strain added to the 25th cycle. It is conceivable, within the limits
of the test procedure and accuracy of measuring, that no sensible creep developed
after the first five cycles.

Apparently 0.118 percent strain occurred after the first five cycles with but a
maximum addition of 0.003 percent strain on subsequent thermal cycling. Total
time at elevated temperature could not have been greater than 60 minutes. Con-
sider that specimens constantly loaded at 29,000 psi for 300°F and 600°F indicate
strain rates of 10^{-5} percent per hour. It is conceivable that no sensible creep
strain was measured and that this is directly in accord with the constantly loaded
creep strain data.

Fracture Toughness

Specimens were fabricated in accordance with dimensional requirements shown in
EM B1-M1-2. Part-through-the-thickness surface flaws were eloxed followed by
chem-etching. Precracking of the specimens by means of fatiguing proved to be
a difficult process. Previous experience indicated optimum conditions for pre-
cracking would be at 800°F for cyclically loading within prescribed limits. Un-
fortunately, the time consumed for this process procedure was inordinate, a dis-
proportionate amount of time was used. A decision was made to mechanically
damage the rest of the notch by means of a sharp edged X-acto knife. Table 11
contains data and specifics for this segment of the test program. Using Irwin's
analysis for calculating fracture toughness for sheet H1510 with the flaw normal
to the transverse direction, the fatigued precracked K has been calculated to be
approximately 10,000 psi √in. This is in contrast to the small differential for the
mechanically damaged flaw which indicated calculated K from 14,700 to 16,600
psi √in. for the balance of tests. The specimens which were fatigued at 800°F
were not disassembled and examined for crack growth prior to fracture, but were
allowed to cool to room temperature in the test set-up, then tensilely loaded to
fracture. Specimens 2ATKR4 and 5 reveal very little fatigue growth. It is con-
jectured that fatigue at 800°F would develop a layer of plastic zone ahead of the
flaw which in turn could provide for higher fracture toughness, which was not
observed. Secondly, the mechanically damaged twinned structure would theo-

retically have lower fracture toughness than calculated because of the depth
of twinned structure was not added to the depth dimension "a" for calulation of
"K". Consequently, at this time it appears (1) evaluation of K is dependent upon
method of creating the flaw, (2) the data may be interpreted as valid for applica-
tion to flaws or imperfections created by means of similar processing histories.

Young's Modulus of Elasticity

Data for the precision modulus of elasticity is shown in Table 12. The specimens
were prestrained prior to strain gaging in addition to straining with strain gages
installed before commencement of strain readings for determination of modulus.
Micromeasurement strain gages model EA 06-250BG-120 for a 0.25-in. gage
length were applied with Eastman 910 adhesive. Full bridge averaging of two
strain gages were used to enhance accuracy. Data were not confirmed by means
of Tuckerman optical strain gage techniques. Specimens were fabricated to the
configuration specified in EM B1-M1-2.

Fatigue Testing

Tables 13 and 14 contain the stress-cycle data for the exposure of the 0.120" and
0.140" beryllium sheet specimens from sheets H1514 and H1532, exposed to the
minimum to axial stress ratio of R = .2. Similarly, Figures 23 and 24 graphically
illustrates the stress to number of cyles of test for endurance limits.

Fatigue testing was performed in a constant amplitude 10 KIP resonant fatigue
Lockheed designed machine at frequencies ranging from 2015 to 2475 cpm and at
a stress range ratio of + 0.1. Each test data point was plotted on a working curve,
and testing was concluded when the fatigue properties were reasonably defined.
Fatigue specimens were prepared in accord with requirements shown in EM
B1-M1-2.

Three Point Bending Test

The configuration used for the three point bending test is shown in EM B1-M1-2.
Load was applied through .187" radius dowels using a constant cross-head rate
of 0.05 in./min. Displacements of the cross-head on the 60,000 lb capacity
Riehle testing machine were autographically measured with a microformer deflec-
tometer and recorder within 0.001 in. of deflection measurements made at the
center of the span measured by means of a dial gage. Typical deflection and
measurement curves are shown in Figures 25 and 26. By extrapolation
of the modulus line to the failure load, both elastic and plastic deflections may be
read on the load-deflection curves. Calculation applicable to any particular de-
flection may be accomplished by dividing the deflection by the half span to deter-
mine the angle whose tangent is in agrement with the deflection/half span width
ratio. Twice the calculated angle is the bend angle.

Data obtained for the three point bend tests at room temperature, 300°F and 600°F, are shown in Tables 15, 16, and 17, respectively.

Heating of the specimens was in a Marshall furnace controlled to ± 3°F.

Charpy V-Notch Testing

Impact testing was performed on 0.120-inch sheet H-1510 and 0.140-inch sheet H-1535 in both the longitudinal and transverse orientations. Testing was performed on duplicate specimens at room temperature, 300°F and 600°F. Specimens were fabricated in accordance with dimensions shown in EM B1-M1-2. Specimens for elevated temperature testing were heated in an air circulating thermocuple-mounted furnace with a one-inch thick copper hearth. Tongs and specimens were placed on the copper hearth. Tongs and specimens were placed on the copper hearth. Tests were completed within three seconds on removal from the furnace.

Impact test data for RT, 300°F and 600°F is listed in Table 18, and graphically illustrated in Figure 27. As the temperature rises, data trend indicates increasing toughness for the longitudinal orientation versus a relatively low increase for the transverse orientation.

Impact testing of the beryllium sheet Charpy-V Notch specimens was performed on a Man Labs, Inc. impact testing machine with a 24-ft-lb capacity. The machine employs a compound pendulum design which ensures extreme rigidity and minimizes possibility of specimen "jamming." Sensitivity of the machine is better than 0.02 ft-lbs. The striking velocity of the top is approximately 11.5 ft per second. In testing, the specimen is placed squarely on the anvil using centering tongs. A pointer measures the residual angular displacement of the pendulum to the nearest 0.1 degree. This angle, α, is then converted to energy lost by the pendulum (i.e., absorbed by the specimen).

$$W = 11.8472 + 12.03\ (\cos\alpha)$$

$$W = \text{energy -- ft-lbs}$$

$$\alpha = \text{residual angle, degrees}$$

Metallography

Figures 28, 29 and 30 illustrate the microstructure for a sheet from each of the three pressings. A quantitative grain size count was made as prescribed in ASTM-E112-63 using the Heyn or Intercept Procedure. Results of the count are as follows:

Sheet	Pressing	Grains/MM^3	Approx. ASTM Micro Grain Size	Approx. Grain* Configuration
H1514	379P	1,100,000	10.4	{ 2.1:1 (a) { 1.8:1 (b)
H1532	432P	789,900	10.1	{ 1.6:1 (a) { 1.4:1 (b)
H1516	395P	1,460,000	10.7	{ 1.8:1 (a) { 1.6:1 (b)

*Indicates average grain configuration with normal dimension of
grain as referenced (ASTM E112-63 PP 7.4).

a) $nm/n\ell$

b) nm/n_t

The analysis was made as described below:

(1) From observation of photomicrographs, specimens examined exhibit grain
orinetation (non-equiaxial) as shown in the schematic diagram below:
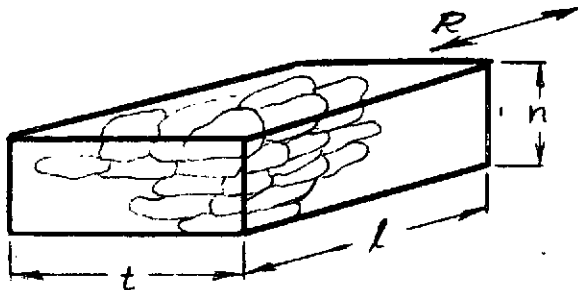
n = normal direction

ℓ = long direction

t = transverse direction

R = rolling direction

(2) Heyn intercept formula for non-equiaxial grain size: (ASTM E112-63, Para.
7.3, 7.4, and Graph 2) yields applicable formula:

$$n_{\ell tn} = 0.7 \times n_\ell \times n_t \times n_n$$

where:

$n_{\ell th}$ = grains/min^3

n_ℓ = grains/min long direction

n_t = grains/min trans direction

n_n = grains/min normal direction

0.7 = correction factor for non-
equiaxed grains

Table 1
CHEMICAL ANALYSIS OF CROSS-ROLLED BERYLLIUM SHEET

Gage	0.140 in.	0.124 in.	0.140 in.
Pressing	432P	379P	395P
Be Assay	98.83	99.00	99.10
Be O	1.24	1.04	1.02
C	.062	.048	.050
Fe	.097	.095	.090
Al	.052	.042	.030
Mg	.019	.004	.012
Si	.024	.016	.028
Ni	.021	.013	.017
Mn	.014	.022	.031
Cr	.013	.016	.014
Ca	.020	<.020	<.020
Co	<.0005	<.0005	<.0005
Cu	.008	.009	.009
An	<.010	<.010	<.010
Ag	<.0001	<.001	<.0001
Pb	<.0001	.0003	.0002
Ti	.015	.015	.024
Mo	<.001	<.001	<.001
N	.020	.02	.023

LAC 07-4008A CHEMISTRY REQUIREMENTS

Composition	Percent by Weight
Beryllium assay	98.00 minimum
Beryllium oxide	2.00 maximum
Aluminum	0.18 maximum
Carbon	0.15 maximum
Iron	0.18 maximum
Magnesium	0.08 maximum
Silicon	0.08 maximum
Other metallic impurities, each	0.04 maximum

Table 2

PRODUCER'S ROOM TEMPERATURE
TENSILE STRENGTHS
CROSS-ROLLED BERYLLIUM SHEET

Pressing	Sheet	Gage (in.)	Longitudinal UTS (ksi)	Longitudinal TYS (ksi)	Longitudinal Elong (%)	Transverse UTS (ksi)	Transverse TYS (ksi)	Transverse Elong (%)	Fe /Al	E.M.-M1-B1 Sheet Designation
379P	H-1509	0.124	79.9	58.6	23.0	76.4	64.9	13.0	2.26	
379P	H-1510	0.124	74.6	60.6*	12.0	74.6	60.1	20.0	2.26	Ia
379P	H-1511	0.124	76.0	58.8	20.0	76.2	57.5*	30.0	2.26	Ic
379P	H-1512	0.124	76.4	60.6	21.0	75.8	62.5*	28.0	2.26	
379P	H-1514	0.124	79.4	60.2	23.0	77.2	58.9*	35.0	2.26	Ib
395P	H-1518	0.140	77.1	54.8	21.0	73.1	54.1	22.0	3.0	IIIa
395P	H-1515	0.140	75.4	56.4	11.0	75.3	53.2	21.0	3.0	
395P	H-1516	0.140	73.3	55.7	12.0	78.3	58.2	28.0	3.0	IIIb
395P	H-1517	0.140	75.2	56.8	18.0	75.6	53.7	26.0	3.0	IIIc
432P	H-1532	0.140	72.1	53.9	9.0	74.2	54.3	19.0	1.86	IIb
432P	H-1533	0.140	71.0	50.5	11.0	71.1	52.3	15.0	1.86	
432P	H-1534	0.140	71.9	50.3*	11.0	71.2	53.1	14.0	1.86	IIc
432P	H-1535	0.140	71.2	51.1	12.0	72.2	51.1	23.0	1.86	IIa
432P	H-1536	0.140	76.6	55.9	15.0	73.4	53.0	19.0	1.86	
432P	H-1537	0.140	76.6	56.8	14.0	72.7	55.6	17.0	1.86	

*Drop-of-the-beam, yield strengths are < 2000 psi from yield point.

LAC 07-4008A MECHANICAL PROPERTY REQUIREMENTS

Nominal Thickness, (inch)	Tensile Strength, Minimum (psi)	Yield Strength at 0.2% Offset, Minimum (psi)	Elongation Minimum (% in 2 in.)
Under 0.250	70,000	50,000	5

TABLE 3

PROGRAM OUTLINE FOR TENSILE TEST SPECIMENS

PRESSING	SHEET	ROOM TEMP		300°F		600°F	
		L	T	L	T	L	T
379P	H1510	3	3	3	-	-	3
	H1514	-	-	-	3	3	-
	H1511	1	-	-	3	-	3
432P	H1535	-	-	3	-	3	-
	H1532	1	1	-	3	-	3
	H1534	1	1	-	3	-	3
395P	H1518	-	1	3	-	3	-
	H1516	-	-	-	3	-	3
	H1517	3	-	-	3	3	3

L = Longitudinal

T = Trausuerse

TABLE 4(a)

TABLE 4(a)

80 COLUMN WORK SHEET

REMARKS

1. BUCKLED IN TEST
2. FAILED OUTSIDE GAGE LENGTH
3. SINGLE POLISH AND ETCH
4. DOUBLE POLISH AND ETCH
5. PREMATURE FAILURE-UNDERCUT

									TENSILE TEST DATA									COMPRESSION TEST DATA			
GAGE (INCH)	PRESSING SHEET	PRODUCT IDENTITY (HEAT)	HEAT (SHEET)	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH MN/m²	KSI	TENSILE YIELD POINT MN/m²	KSI	TENSILE YIELD STRENGTH MN/m²	PSI	ELONGATION % in 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSIVE YIELD STRENGTH MN/m²	KSI		
.124	T	α 379P	H1510	T	RT	KBI-H1510	517	74.6	—		512	60.1	20.0		2ATCR1	453	63.5		
						2ATTR1	—	64.1	440	63.8	429	62.1	3.0	5	2ATCR2	428	61.9		
						2ATTR2	522	75.4	442	64.0	415	60.2	25.0		2ATCR3	438	63.4		
						2ATTR3	521	75.4	428	62.0	417	60.4	18.0		LMSC-AV	436	62.6		
						LMSC-AV	520	75.4	435	63.3	420	60.9	21.5		2ATC34	407	58.7		
				300°F											LMSC	467	52.5		
				600°F	2ATT64	312	45.1	321	46.9	321	46.1	42.0		2ATC65	368	44.6		
					2ATT65	318	45.7	311	44.7	305	43.4	42.0		2ATC66	307	44.0		
					2ATT66	326	47.3	334	47.8	325	46.7	45.0		LMSC-AV	301	44.7		
					LMSC-AV	318	46.0	315	46.5	318	45.4	43.1						
				L	RT	KBI-1510	517	74.6			418	60.6	12.0		—	—			
						2ALTR1	489	70.7	440	63.8	423	61.6	5.5	2,3					
						2ALTR2	532	77.0	452	65.4	421	61.1	15.0	4					
						2ALTR3	537	77.5	437	63.4	427	61.7	14.0	3					
						LMSC-AV	537	75.1	442	64.2	422	61.5	14.0						
				300°F	2ALT31	445	64.6	405	58.3	400	57.6	60.0	3	2ALC31	405	58.4		
					2ALT32	452	65.5	390	56.6	391	56.4	62.0		2ALC32	—	—		4
					2ALT33	455	65.9	408	58.7	403	58.3	63.0		2ALC33	413	59.4		
				600°F	LMSC-AV	451	65.3	402	57.9	397	57.4	61.7		LMSC-AV	409	58.9		
															2ALC64	361	43.4		
															2ALC65	310	44.6		
															2ALC66	313	45.4		
					LMSC-AV										LMSC-AV	308	44.5		

TABLE 4(b)

C-12

REMARKS

1. BUCKLED
9. SOME BENDING IN FIXTURE
5. PIECE MISSING FROM FRACTURE

80 COLUMN WORK SHEET

GAGE (INCH)	PRESSING SHEET	E.H. M1-B1	PRESSING HEAT	PRODUCERS IDENTITY HEAT SHEET	ORIENTATION	TEMPERATURE (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH		TENSILE YIELD POINT		TENSILE YIELD STRENGTH		ELONGATION (IN 1")	REMARKS	SPECIMEN IDENTITY	COMPRESSIVE YIELD STRENGTH	
								MN/m²	KSI	MN/m²	KSI	MN/m²	KSI				MN/m²	KSI
.124	I	b	379P	H1514	T	RT	KB1-H1514	551	77.2	—	—	410	58.9	35				
																2BTCR1	405	58.7
																2BTCR9	407	58.6
																LMSC-AV	406	58.7
						300°	28TT34	429	62.2	398	57.2	390	56.1	53	Ⓒ	28TC33	375	55.7
							28TT35	429	62.2	394	57.3	384	55.6	52		28TC34	377	54.6
							28TT36	433	62.7	392	57.0	391	56.3	49		28TC35	386	55.6
							LMSC-AV	430	62.4	398	57.2	389	56.0	51.5		LMSC-AV	381	55.4
						600°										28TC66	410	59.4
																28TC67	431	60.5
																28TC68	442	62.3
																LMSC-AV	288	41.7
					L	RT	KB1-H1514	550	79.4	—	—	416	60.2			2BLCR1	—	—
																2BLCR6	420	60.7
																LMSC-	420	60.7
						300°F										28LC32	387	56.6
																28LC33	391	56.7
																LMSC-AV	389	56.7
						600°F	2BLT64	323	46.5	323	46.5	318	45.6	64.0		2BLC64	302	43.8
							2BLT65	325	46.5	332	47.9	317	45.5	71.0		28LC65	316	45.8
							2BLT66	324	45.4	330	47.6	320	45.0	73.0		LMSC-AV	309	44.7
							LMSC-AV	324	46.4	329	47.4	319	45.7	70.7				

TABLE 4(c)

9" COLUMN WORK SHEET

REMARKS

5. LAST PIECE IN FRACTURE
6. SPECIMEN SLIPPED—DISCARDED
7. BROKE AT EXTENSO-METER KNIFE EDGE

GAGE (INCH)		HEM MI-BI	PRODUCERS IDENTITY	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH		TENSILE YIELD POINT		TENSILE YIELD STRENGTH		ELONGATION % IN 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH		REMARKS
							MN/m²	KSI	MN/m²	KSI	MN/m²	KSI				MN/m²	KSI	
.124	I	C	379P	H 1511	T	RT	KBI-H1511	525	76.2	—	—	397	57.5	30.0		2CTICR1		612	
																2CTICR2		623	
																2CTICR3		607	
																LMSC-AV		617	
					300°F	2CTT31	432	63.1	410	59.0	395	57.1	52.0					
						2CTT32	424	61.8	396	57.4	389	56.1	41.0	⑥				
						2CTT33	428	62.3	411	59.2	392	56.6	48.5					
						LMSC-AV	424	62.4	403	58.5	392	56.6	49.8					
					600°F	2CTT64	330	47.5	342	49.7	331	47.5	58.5					
						2CTT65	—					—	—	⑥				
						2CTT66	331	47.8	341	49.5	322	46.4	56.5					
						LMSC-AV	319	47.6	342	49.6	327	47.0	57.5					
					L	RT	KBI-H1511	521	76.0	—	—	410	58.8	20.0					
							2CLTR1	475	65.3	424	61.4	418	60.0	55	⑦	2CICR1		618	
															2CICR2		629	
															2CICR3		625	
															LMSC-AV		621	
					300°F													
					600°F													

TABLE 5 (a)

REMARKS

7. BROKE IN TEST SETUP
8. INSTRUMENTATION WENT OUT -- TOO HIGH READING

80 COLUMN WORK SHEET

GAGE (INCH)	E.H. Hi-Bi	PRESSING SHEET	PRESSING CHART	PRODUCER IDENTITY HEAT	(SHEET)	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH MN/m²	KSI	TENSILE YIELD POINT MN/m²	KSI	TENSILE YIELD STRENGTH MN/m²	KSI	ELONGATION %/in 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH MN/m²	KSI	REMARKS
.140	II	a	432P	H N35	T	RT	KBI-HN35	50	72.2	—	—		51.1	23.0						
							300°									4ATC31	—	—	(8)	
																4ATC32	320	46.7		
																4ATC33	319	46.3		
																LMSC-AV	319	46.5		
							600°F													
						L	RT	KBI-HN35	490	71.2			355	51.1	12.0					
							300°	4ALT34	—	—	—	—	—	—	(7)	4ALC31	337	48.9		
								4ALT35	422	61.2	328	47.4	327	47.3	67.0	4ALC32	339	49.2		
								4ALT36	410	61.0	341	49.4	333	48.1	61.0	4ALC33	350	50.2		
								LMSC-AV	421	61.1	335	48.8	330	47.4	64.0	LMSC-AV	347	49.6		
							600°		190	43.9	281	40.3	277	40.2	37.7					
								4ALT68	310	44.9	280	40.6	270	51.0	13.0					
								4ALT69	308	44.2	300	43.3	280	40.5	21.0					
								LMSC-AV	309	44.3	287	41.3	275	39.9	23.3					

TABLE 5 (b)

REMARKS

1. BUCKLED

80 COLUMN
WORK SHEET

									TENSILE TEST DATA								COMPRESSION TEST DATA	
GAGE (INCH)	TESTING M1-B1	EM M1-B1	PRODUCT IDENTITY PRESSURE	HEAT (HEAT)	HEAT (SHEET)	ORIENTATION	TEMPERATURE °F	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH MN/m²	KSI	TENSILE YIELD POINT MN/m²	KSI	TENSILE YIELD STRENGTH MN/m²	KSI	ELONGATION % in 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH MN/m²	KSI
.120	T	b	432P	H1532	T	RT		KB1-H1532	515	74.2			530	34.3	19.0				
								4BLTR1	Y81	70.2	365	52.5	354	51.1	15.0	4B1CR1			49.1
																4B1CR2			50.2
																4B1CR3			52.2
																LMSC-AV			50.4
						418°K 300°F		4BTT34	400	57.5	—	—	325	46.9	39.0	4BTC34	333		47.6
								4BTT35	392	56.6	347	46.4	319	45.9	37.0	4BTC35	330		47.8
								4BTT36	398	57.3	336	48.3	326	47.0	41.0	4BTC36	322		47.0
								LMSC-AV	396	57.1	328	47.3	323	46.6	39.0	LMSC-AV	330		47.8
						533°K 500°F		4BTT67	289	41.9	269	38.5	265	38.7	9.0	4BTC67			38.0
								4BTT68	290	42.3	272	39.4	269	38.8	9.0	4BTC68			36.9
								4BTT69	293	42.4	287	41.4	275	39.7	9.0				
								LMSC-AV	291	42.2	277	39.8	270	38.8	9.3	LMSC-AV			37.4
						L	RT	KB1-H1532	500	72.1	—	—	370	53.9	9.0				
								4BLTR1	486	103	346	79.0	333	48.4	8.5	4B1CR1			51.2
																4B1CR2			50.1
																4B1CR3			
						418°K 300°F										LMSC-AV			50.0
																4BLC34	335		48.0
																4BLC35	339		48.4
																4BLC36	347		50.2
						593°K 600°F										LMSC-AV	340		48.9
																4BLC67			37.0
																4BLC68			37.1
																LMSC-AV			37.0

TABLE 5 (c)

80 COLUMN WORK SHEET

		TENSILE TEST DATA									COMPRESSION TEST DATA		

GAGE (INCH)	SPECIMEN SHEET	MI-B1 PRESSING (CHART)	PRODUCER IDENTITY HEAT (SHEET)	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH MN/m²	KSI	TENSILE YIELD POINT MN/m²	KSI	TENSILE YIELD STRENGTH MN/m²	KSI	ELONGATION % in 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH MN/m²	KSI	REMARKS
.140	II	e	432P H1534	T	RT	KB1-H1534	498	71.2	—	—	367	53.1	14.0					
						4CTT1	455	65.9	333	48.2	330	47.7	13					
					300°F	4CTT34	405	58.4	339	48.6	331	48.0	38.0		4CTC34	348	49.9	
						4CTT35	400	57.8	325	47.0	320	46.1	39.0		4CTC35	337	48.5	
						4CTT36	405	58.4	343	49.4	322	46.5	40.0		4CTC36	349	50.1	
						LMSC-AV	403	58.2	336	48.3	326	46.9	39.0		LMSC-AV	345	49.2	
					600°F	4CTT67	289	41.9	268	38.9	267	38.7	43.0		4CTC67	263	37.6	
						4CTT68	293	42.1	288	41.2	271	39.0	43.0		4CTC68	258	37.3	
						4CTT69	290	42.1	269	38.6	266	38.1	43.0		4CTC69	258	37.3	
						LMSC-AV	291	42.2	275	39.6	268	38.6	43.3		LMSC-AV	259	37.4	
				L	RT	KB1-H1534	495	71.9	—	—	349	50.3	11.0					
						4C1	528	76.4	494	56.5	374	54.1	12.2		4C1CR1	380	54.7	
															4C1CR2	373	54.0	
															4C1CR3	331	54.5	
															LMSC-AV	379	54.5	
					300°F													
					600°F	4CT												

TABLE 6 (a)

80 COLUMN WORK SHEET

TENSILE TEST DATA | **COMPRESSION TEST DATA**

GAGE (INCH)	EM. M1-B1	SHEET PASSING	PRODUCT IDENTITY (HEAVY)	HEAT (SHEET)	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH		TENSILE YIELD POINT		TENSILE YIELD STRENGTH		ELONGATION (in 1")	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH		REMARKS
								MN/m²	KSI	MN/m²	KSI	MN/m²	KSI				MN/m²	KSI	
140	m	a	315P	H1518	T	RT	KB1-H1518	508	73.1	—	—	377	54.1	22.0					
							43 ALT??	513	7.12	400	57.8	388	56.0	13.0		43ATCR1	401	58.2	
																43ATCR2	4??	59.2	
																43ATCR3	410	59.0	
																LMSC-AV	410	59.0	
						428°K / 500°F										43ATC34	367	50.4	
																43ATC35	325	???	
															L	43ATC36	371	???	
																LMSC-AV	375	???	
						593°K / 600°F													
					L	RT	KB1-H1518	538	77.1	—	—	380	55.8	21.0					
																43ALCR1	405	58.6	
																43ALCR2	410	59.6	
																43ALCR3	4??	58.4	
																LMSC-AV	409	58.7	
						428°K / 500°F	43ALT34	450	64.9	387	55.8	381	54.7	54.0					
							43ALT35	448	64.7	38?	55.0	371	53.4	51.5					
							43ALT36	450	64.9	389	55.4	379	54.?	53.0					
							LMSC-AV	449	64.8	386	55.6	377	54.?	52.8					
						593°K / 600°F	43ALT67	325	47.?	331	47.?	311	45.?	72.0		43ALC64	29?	42.2	
							43ALT68	32?	46.7	32?	47.0	305	44.1	70.0		43ALC65	29?	42.?	
							43ALT69	3??	47.?	320	4?.?	308	44.6	70.?		43ALC66	30?	43.4	
							LMSC-AV	32?	47.?	3??	47.0	308	44.6			LMSC-AV	299	42.6	

TABLE 6 (b)

80 COLUMN WORK SHEET

MI	ORGN	O.G.	PA	PAGE OF	PROGRAMMER		ORGN	EXT	JOB NO	REQUEST DATE	DISPATCH NO	PROGRAM DESCRIPTION								

TENSILE TEST DATA — **COMPRESSION TEST DATA**

GAGE (INCH)	FLOW DIRECTION / SHEET	E.M. (M-B) / PRESSURE (HEAT)	PRODUCER IDENTITY HEAT (SHEET)	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH MN/m²	KSI	TENSILE YIELD POINT MN/m²	KSI	TENSILE YIELD STRENGTH MN/m²	KSI	ELONGATION % in 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH MN/m²	KSI	REMARKS
.140		6	54M	H1316	RT	KB1-H1316	543	78.3	—	—	405	58.2	28.0					
															43BTCR1	403	58.0	
															43BTCR2	411	59.2	
															43BTCR3	412	59.5	
					43AF 300°F										Lmse-Av	409	58.4	
						43BTT34	420	60.5	380	54.5	360	51.4	47.0					
						43BTT35	420	60.5	—	—	371	53.1	45.0					
						43BTT36	427	61.1	385	55.3	365	52.8	48.0					
						Lmse-Av	421	60.7	382	54.9	364	52.4	46.7					
					593°K 608°F	43BTI67	314	45.3	310	44.9	301	43.3	52.0					
						43BTI68	316	45.7	331	47.4	319	46.0	51.0					
						43BTI69	314	45.5	320	46.0	310	44.9	50.0					
						Lmse-Av	314	45.5	321	46.3	307	44.7	51.0					
					RT	KB1-H1316	511	73.3	—	—	388	55.7	12.0					
															43BLCR1	410	59.2	
															43BLCR2	410	59.0	
															43BLCR3	408	59.0	
					43AF 300°F										Lmse-Av	409	59.1	
															43BLC34	387	55.4	
															43BLC35	379	54.7	
															43BLC36	369	53.8	
					593°K 608°F										Lmse-Av	377	54.3	

TABLE 6 (c)

80 COLUMN WORK SHEET

GAGE (INCH)	TENSILE M1-81 SHEET	PRODUCER IDENTITY	ORIENTATION	TEMPERATURE °K (°F)	SPECIMEN IDENTITY	ULTIMATE TENSILE STRENGTH (MN/m²)	(KSI)	TENSILE YIELD POINT (MN/m²)	(KSI)	TENSILE YIELD STRENGTH (MN/m²)	(KSI)	ELONGATION % in 1"	REMARKS	SPECIMEN IDENTITY	COMPRESSION YIELD STRENGTH (MN/m²)	(KSI)	REMARKS
.40 TI	c	3?5 P	H.??	T	N'T	KB1-M1?7	521	76.6	—	—	369	53.7	26.0					
															43C?CR1	401	5?9	
															43C?CR2	403		
															43C?CR3	401	?.?	
															LMSC AV	402		
				420°K (300°F)	43CTT31	425	61.7	389	56.3	371	53.6	53.0					
					43CTT32	423	61.1	383	55.1	379	53.0	38.0					
					43CTT33	426	61.9	386	55.4	374	53.9	45.0					
					LMSC-AV	425	61.6	351	54.9	371	53.5	45.3					
				593°K (600°F)	43CTT64	379	46.0	316	45.1	300	43.3	39.0					
					43CTT65	379	46.0	312	45.3	307	43.9	50.0					
					43CTT66	330	46.1	302	44.1	301	43.4	36.0					
					LMSC AV	379	46.0	311	45.0	307	43.5	41.7					
			L	RT	KB1-M1?7	522	75.?	—	—	392	56.8	18.0					
															43C?CR1	399	5?4	
															43C?CR2	401	5?6	
															43C?CR3	398	5?3	
				420°K (300°F)											LMSC AV	399	?.?	
															43C?C34	361	5?8	
															43C?C35	350	50.?	
															43C?C36	365	?.?	
				593°K (600°F)	43CLT67	322	46.8	307	44.v	296	42.8	48.0		LMSC-AV	360	5?.?	
															43C?C67	28?	40.?	
					43CLT68	329	47.4	32.1	46.8	305	44.3	72.0		43C?C68	2?8	41.?	
					43CLT69	329	47.4	314	45.5	301	44.7	64.0		43C?C69	2?0	41.7	
					LMSC-AV	326	47.v	315	45.6	301	43.9	48.0		LMSC-AV	2?5	41.1	

TENSILE TEST DATA — COMPRESSION TEST DATA

TABLE 7 - MECHANICAL PROPERTIES

PROPERTY		R.T. A	R.T. B	R.T. (MIL-B-8694) A	R.T. (MIL-B-8694) B	300° A	300° B	600° A	600° B
F_{TU}, KSI	L	64	68	65	70	56	59	41	43
	T	66	69	65	70	53	56	41	43
F_{TY}, KSI	L	40	46	43	49	36	42	34	38
	T	40	47	43	49	37	43	31	35
F_{CY}, KSI	L	44	49	--	--	40	45	38	40
	T	45·	50	--	--	36	42	30	33
E_{LONG}, % in 1 in.	L	--	5	4		36	45	60	64
	T	--	6	4		27	35	27	35

TABLE 8

PROGRAM OUTLINE FOR COMPRESSION YIELD TEST SPECIMENS

PRESSING	SHEET	ROOM TEMP		300° °F		600° °F	
		L	T	L	T	L	T
379P	H1510	-	3	3	1	3	2
	H1514	2	2	2	3	2	3
	H1511	-	-	-	-	-	-
432P	H1535	-	-	3	3	-	-
	H1532	-	-	-	3	-	3
	H1534	3	-	-	3	-	3
395P	H1518	3	3	-	3	3	-
	H1516	3	3	3	-	-	-
	H1517	3	3	-	-	3	-

TABLE 9

BERYLLIUM SHEET - LONGITUDINAL

STATIC CREEP DATA

Specimen Identity	Sheet Number	Test Temperature (^{o}F)	Stress Level (psi)	Test Duration (hours)	Creep Strain (%)	Strain Rate Per Hour
2ALS31	H1510	300	45000	100	0.020	1.6×10^{-6}
2ALS32	H1510	300	55000 (*)	15	9.0	1.3×10^{-3}
2ALS33	H1510	300	29000	100	0.007	6.4×10^{-7}
2ALS64	H1510	600	40000	100	0.09	2.1×10^{-6}
2ALS65	H1510	600	29000	100	0.014	4.5×10^{-7}
2ALS66	H1510	600	50000(**)	-	--	-
4ALS31	H1535	300	33000	100	0.010	7.5×10^{-7}
4ALS32	H1535	300	45000	100	9.0	7.0×10^{-4}
4ALS32	H1535	300	45000	300	32.7	-
4ALS33	H1535	300	20000	100	(****)	-
4ALS64	H1535	600	29000	100	0.020	6.3×10^{-7}
4ALS64	H1535	600	29000	300	0.029	-
4ALS65	H1535	600	38000(***)	5.9	7.9	9.5×10^{-3}
4ALS66	H1535	600	20000	100	0.016	7.8×10^{-7}

(*)   Ruptured @ 20.6 hours
(**)   Failed on loading
(***)   Ruptured @ 7.4 hours
(****) No detectable creep

MECHANICAL PROPERTIES

Temperature ^{o}F	Sheet	UTS		TYS		ELONG	
		L KSI	T KSI	L KSI	T KSI	L %	T %
300°	H1510	65.3	-	57.4	58.5*	62	-
	H1535	-	-	49.6*	46.5*	-	-
600°	H1510	-	46.0	44.4*	45.4	-	43
	H1535	44.3	-	39.9	-	70	-

* CYS

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TABLE 10

CREEP OF BERYLLIUM UNDER PROFILE CONDITIONS

Constant 29,000 psi 75F to 600F in 3 min.

2.0 in Gage Length

Specimen No.2ALP1 Longitudinal from sheet H1510, Pressing 379P

No. of Cycles	Length Fiducial Marks Numbered Side	Average of 3 Readings Reverse Side		Extension in in.
0	2.00213	1.99677		
5	2.0044	1.99683		
	2.0021	1.99677		
	+0.0023	+ .00006	=	.00236
				0.1182% creep
15	2.00393	1.99737		
	2.00210	1.99677		
	+0.00183	+ .00060	=	+ 0.00243
				0.121% creep
25	2.0035	1.9976		
	2.0021	1.9967		
	+ .0014	+ .0009	=	+ 0.0023
				0.115% creep

Total % creep in one inch after 25 cycles 0.118% avg.

TABLE 11

BERYLLIUM SHEET FRACTURE TOUGHNESS

Pressing	Sheet	Spec. No.	W	t	A	Pmax	σ_{max}	ao	Co	ao/Co	ϕ^2	Q	IRWIN K	NOTES
		2ALKR1	1.498	0.1170	0.175	7560[b]	43,200	0.010	0.035	0.286	1.19	1.090	8,034	(a)[b]
		2ALKR2	1.500	0.1184	0.178	9470	53,202	0.019	0.278	0.068	1.02	0.8681	15,282	(a)
		2ALKR3	1.498	0.1161	0.174	9730	55,919	0.021	0.261	0.080	1.025	0.8572	16,994	(a)
2701	IC510	2ATKR4	1.500	0.1180	0.177	6110	34,520	0.022	0.263	0.084	1.028	0.9625	10,133	(c)
		2ATKR5	1.500	0.119	0.178	5830	32,753	0.028	0.265	0.106	1.040	0.981	10,744	(d)
		2ATKR6	1.496	0.1184	0.177	2140	12,090	0.029	0.259	0.112	1.043			(e)
		4ALKR1	1.500	0.1381	0.207	9140	44,154	0.032	0.257	0.124	1.050	0.8494	16,640	(a)
		4ALKR2	1.500	0.1380	0.207	8790	42,464	0.030	0.265	0.113	1.044	0.8585	15,413	(a)
4?P	H1535	4ATKR3	1.499	0.1364	0.204	8170	40,049	0.032	0.224	0.143	1.062	0.8956	14,699	(a)
		4ATKR4	1.494	0.1368	0.204	8750	42,892	0.031	0.246	0.126	1.052	0.8628	15,736	(a)

NOTES:

(a) Specimen notch root scribed with x-acto blade at RT

(b) Specimen broke at locus of percussion welded thermocycle. Dimensions of flaw origin too uncertain to compare results with controlled surface flawed specimens

(c) Specimen fatigued in tension - tension at Pmax = 3200 lbs, R = +0.1, for 60,000 cycles at 800°F; tested at RT

(d) Specimen fatigued in tension - tension at Pmax = 2695 lbs, R = +0.1 for 60,000 cycles at 800°F; tested at RT

(e) Spec. fatigued in tension - tension at Pmax = 3205 lbs, R = +0.1 for 110,000 cycles at 800°F then 55,000 cycles at 900°F; tested at RT, failed during loading at RT, but max load not recorded - electronic recording problem.

Eqn used: $K_{calc} = \left[\dfrac{1.2\,(\sigma_{max})^2\, a_o}{\phi^2 - .212\left(\dfrac{\sigma_{max}}{F_{ty}}\right)^2} \right]^{\frac{1}{2}}$ (i.e., Irwin's basic PTC solu)

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TABLE   12

Young's Modulus 78°F

Strain Gage Data

Be Sheet Longitudinal Direction

Spec. No.*	Run No.	Max. Stress (psi)	Young's Modulus 10^6 psi
2ALMR1	1	17,108	42.04
	2	30,794	42.04
	3	34,216	41.47
	4	34,216	41.91
			41.86 Avg.
4ALMR1	1	29,488	41.84
	2	29,488	41.65
	3	29,488	41.30
	4	29,488	41.16
			41.48 Avg.
43ALMR1	1	29,253	41.84
	2	29,253	41.58
	3	29,253	41.58
			41.66 Avg.

* Specimen 2ALMR1 made from beryllium sheet H1510, Pressing 379P

Specimen 4ALMR1 made from beryllium sheet H1535, Pressing 432P

Specimen 43ALMR1 made from beryllium sheet H1518, Pressing 395P

TABLE   13

CONSTANT AMPLITUDE FATIGUE DATA FOR BERYLLIUM SHEET

$(K_t = 2.7, R = + 0.1, t = .120")$

Specimen[**] Number	Max. Stress (Net Area) (ksi)	Cycles	Comments
2BLFR-1	65	Broke on Loading	(-1 rerun)
2BLFR-9	60	54,613	-
2BLKR-8	55	91,683	-
2BLFR-2	50	124,200	-
2BLFR-3	46	163,086	-
2BLFR-10	45	0*	(Fragmented on Loading)
2BLFR-4	44	666,051	-
2BLFR-5	43	1,547,490	-
2BLFR-6	42	2,552,550	-
2BLFR-7	41	2,036,150	-
2BLFR-1	40	11,831,575	No Failure

*   Specimen shattered under 269 lb   of 6750 lb   load.   Failure occurred outside of test area.

**   Specimens made from beryllium sheet H1514, Pressing 379P.

TABLE 14

CONSTANT AMPLITUDE FATIGUE DATA FOR BERYLLIUM SHEET

$$(K_t = 2.7, \ R = + \ 0.1, \ t = .140")$$

Specimen * Number	Max. Stress (Net Area) (ksi)	Cycles	Comments
4BLFR-5	55	22,027	-
4BLFR-2	50	35,275	-
4BLFR-10	48	305,750	-
4BLFR-3	46	90,099	-
4BLFR-8	45	270,115	-
4BLFR-9	45	738,700	-
4BLFR-1	44	1,060,800	-
4BLFR-7	43	1,316,700	-
4BLFR-4	42	4,676,049	-
4BLFR-6	40	10,790,928	No Failure

* Specimens were made from beryllium sheet H1532, Pressing 432P.

TABLE 15

BERYLLIUM SHEET THREE POINT BEND DATA

(Span = 1.500 in; diameter of mandrels = 0.375; speed 0.05 in/min.)

Test Temperature 75°F

Spec.* No.	Thick in.	Width in.	Failure (a) Load (lbs)	Failure (b) Moment (lb-in)	Deflection Mils Elastic	Plastic	Total	Bend Angle Degrees
2ALBR1	.1216	.9922	852	320	.0110	.0110	.0220	3.4
2ATBR1	Broken in Machining							
2BLBR1	.1215	1.0195	840	315	.0100	.0133	.0233	3.6
2BTBR1	.1223	1.123	720	270	.0105	.0110	.0215	3.3
2CLBR1	.1225	.9986	876	329	.0115	.0065	.0180	2.8
2CTBR1	.1189	.9943	769	288	.0125	.0065	.0190	2.9
2ATBR2	.1211	1.0028	816	306	.0120	.0073	.0213	3.3
4ALBR1	.1393	1.0052	1020	383	.0115	.0143	.0258	3.9
4ATBR1	.1391	1.0079	902	338	.0105	.0092	.0197	3.0
4BLBR1	.1365	1.0230	927	348	.0120	.0118	.0238	3.6
4BTBR1	.1406	1.0062	821	308	.0105	.0055	.0160	2.4
4CLBR1	.1313	.9916	934	350	.0115	.0150	.0265	4.0
4CLBR1	.1293	.9877	810	304	.0125	.0091	.0216	3.3
43ALBR1	.1398	.9855	1041	390	.0115	.0112	.0227	3.5
43ATBR1	.1400	.9839	996	374	.0120	.0095	.0195	3.0
43BLBR1	.1389	.9862	1099	412	.0115	.0150	.0265	4.0
43BTBR1	.1387	.9860	942	353	.0100	.0086	.0186	2.8
43CLBR1	.1377	.9775	883	331	.0130	.0090	.0220	3.4
43CTBR1	.1315	.9918	851	319	.0110	.0086	.0190	3.0

(a) Failure load expressed in pounds per inch of width.
(b) Failure moment expressed in lb-in of width Moment = P/2 x 1/2 = 0.375 P where
     P = load, 1 = span in inches.

* Specimens were fabricated beryllium sheets as follows:

      2AXBXX from sheet H1510 pressing = 379P
      2BXBXX from sheet H1514 pressing = 379P
      2CXBXX from sheet H1511 pressing = 379P
      4AXBXX from sheet H1535 pressing = 432P
      4BXBXX from sheet H1532 pressing = 432P
      4CXBXX from sheet H1534 pressing = 432P
      43AXBXX from sheet H1518 pressing = 395P
      43BXBXX from sheet H1516 pressing = 395P
      43CXBXX from sheet H1517 pressing = 395P

TABLE 16
BERYLLIUM SHEET THREE POINT BEND DATA

(Span = 1.500 in; diameter of mandrels = 0.375; speed 0.05 in/min.)

Test Temperature 300°F

Spec. No.	Thick in.	Width in.	Failure (a) Load (lbs)	Failure (b) Moment (lb-in)	Deflection Mils Elastic	Plastic	Total	Bend Angl Degrees
2ATB32	.1219	1.0001	794	298	.009	.012	.021	3.2
2ALB32	.1187	.9926	788	296	.0150	.008	.023	3.5
2BTB32	.1225	1.0170	797	299	.0106	.0114	.022	3.3
2CLB32	.1213	.9994	891	334	.0125	.015	.0275	4.2
2CTB32	.1197	.9949	761	285	.0154	.0096	.250	3.8
4ALB32	.1388	1.0039	1043	391	.0115	.0215	.033	5.0
4ATB32	.1394	1.0081	918	344	.0122	.0140	.0262	4.0
4BLB32	.1368	1.0116	950	356	.012	.0145	.0265	4.0
4BTB32	.1407	.993	935	351	.014	.0094	.0224	3.6
4CLB32	.1312	0.9934	912	342	.0115	.0165	.0280	4.3
4CTB32	.1306	.9890	863	324	.0114	.0166	.028	6.0
43ALB32	.1396	.9833	1073	402	.011	.015	.026	4.0
43ATB32	.1398	.9859	994	373	.0115	.0100	.0215	3.3
43BLB32	.1400	.9862	1075	403	.0125	.0140	.0265	4.0
43BTB32	.1392	.9859	998	374	.0113	.0197	.031	4.7
43CLB32	.1285	.9933	908	341	.0120	.0145	.0265	4.0
43CTB32	.1311	.9766	879	330	.0125	.013	.0255	3.9

(a) Failure load expressed in pounds per inch of width.

(b) Failure moment expressed in lb-in. of width moment = P x 1/2 = 0.375 P
where P = load, 1 = span in inches.

TABLE 17

BERYLLIUM SHEET THREE POINT BEND DATA

(Span = 1.500 in; diameter of mandrels = 0.375; speed 0.05 in/min.)

<u>Test Temperature 600°F</u>

Spec. No.	Thick in.	Width in.	Failure Load (lbs)[a]	Failure Moment (lb-in)[b]	Deflection Mils Elastic	Deflection Mils Plastic	Deflection Mils Total	Bend Angle Degrees
2ALB63	.1176	.9932	705	264	.0170	.0156	.0326	5.0
2ATB63	.1223	1.0015	799	300	.009	.0382	.0382	5.8
2BLB63	.1188	1.0233	888	333	.0115	.0991	.1106	16.3
2BTB63	.1220	1.0113	997	374	.0085	.1986	.2071	37.0
2CLB63	.1220	.9978	832	312	.0095	.0647	.0742	11.3
2CTB63	.1195	.9948	853	320	.0095	.0785	.0880	18.5
4ALB63	.1375	1.0042	1217	456	.0125	.2480	.2605	34.8
4ATB63	.1395	1.0087	1120	420	.0105	.1615	.1720	34.2
4BLB63	.1372	1.0033	949	356	.0095	.0560	.0655	9.9
4BTB63	.1408	1.0009	1038	389	.0100	.0990	.1090	16.2
4CLB63	.1315	.9921	841	315	.0100	.0480	.0580	8.8
4CTB63	.1229	.9891	979	367	.0095	.1481	.1576	22.8
43ALB63	.1395	.9850	1294	485	.009	.209	.2180	30.2
43ATB63	.1398	.9839	1220	458	.010	.146	.1560	22.4
43BLB63	.1390	.9925	1034	388	.011	.038	.0490	7.5
43BTB63	.1390	.9921	1057	396	.105	.054	.0645	9.8
43CLB63	.1283	.9947	1146	430	.105	.245	.2555	34.3
43CTB63	.1314	.9800	1029	386	.105	.1193	.1298	19.1

(a) Failure load expressed in pounds per inch of width.
(b) Failure moment expressed in lb-in of width; Moment = P/2 x 1/2 = 0.375 P where
    P = load, l = span in inches.

TABLE 18

Be Sheet Charpy Data

$78^{\circ}F$

	LONGITUDINAL			TRANSVERSE	
Spec. No.**	FT/LBS	IN/LBS	Spec. No.	FT/LBS	IN/LBS
2ALIR1	.150	1.795	2ATIR1	.080	.961
2ALIR1	.084	1.014	2ATIR2	.093	1.120
Avg.	.117	1.405		.087	1.041
4ALIR1	.272	3.261	4ATIR1	.155	1.854
4ALIR2	.233	2.791	4ATIR2	.145	1.737
Avg.	.253	2.526		.150	1.796

$300^{\circ}F$

	LONGITUDINAL			TRANSVERSE	
2ALI33	.292	3.261	2ATI33	.093	1.120
2ALI34	.439	5.267	2ATI34	.116	1.394
Avg.	.356	4.264		.105	1.257
4ALI33	.466	5.596	4ATI33	.175	2.095
4ALI34	.521	6.256	4ATI34	.145	1.737
Avg.	.493	5.926		.160	1.916

$600^{\circ}F$

	LONGITUDINAL			TRANSVERSE	
2ALI65	.459	5.509	2ATI65	.406	4.872
2ALI66	(1.225)*	(14.704)*	2ATI66	.528	6.341
Avg.	.459	5.509		.467	5.607
4ALI65	(1.007)*	(12.087)*	4ATI65	.266	3.193
4AI66	.693	8.319	4ATI66	.289	3.469
Avg.	.693	8.319		.278	3.331

*off center strike

** Specimens 2ALIXX are from 0.124" Beryllium sheet H1510, pressing 379P

Specimens 4ALIXX are from 0.140" Beryllium sheet H1535, pressing 432P

FIGURE 1

STRESS STRAIN PLOT
Be SHEET SPECIMEN No. 4B TTRI
78°F   TRANSVERSE

FIGURE 2

LOAD STRAIN PLOT
Be SHEET SPECIMEN NO. 4CTT36
300°F TRANSVERSE

T.S. 58.4 KSi

FRACTURE 70.3 KSi

y.s 40.4 KSi

y.s. 46.5 KSi

CROSSHEAD   RATE
0.01 IN/MIN   0.1 IN/MIN

STRAIN   RATE
~ .008 IN/MIN   ~ .08 IN/MIN

LOAD LBS.

STRAIN IN/IN.

C-33

FIGURE 3

LOAD STRAIN PLOT
Be SHEET SPECIMEN NO. 43 CTT 65
600F TRANSVERSE
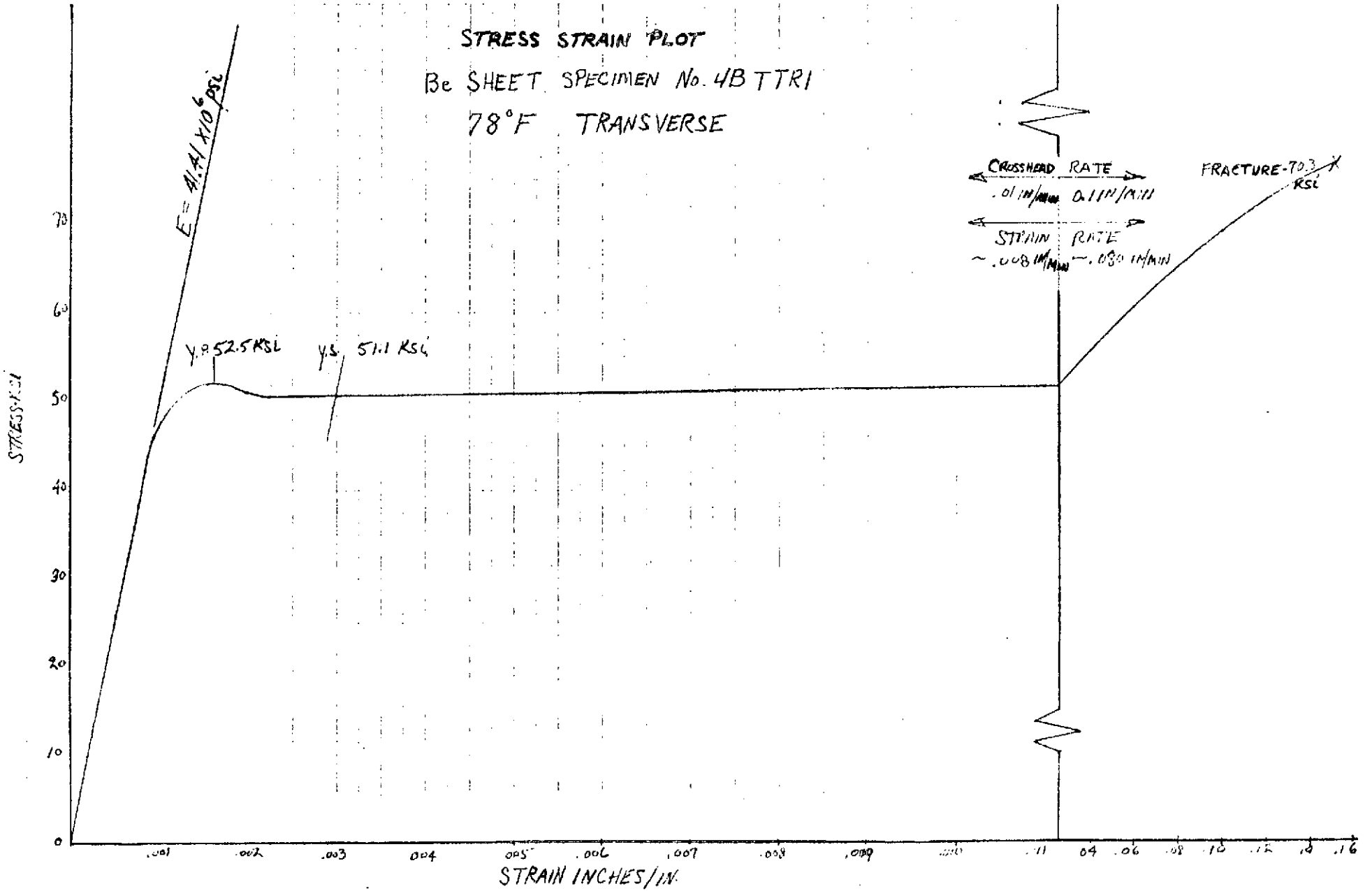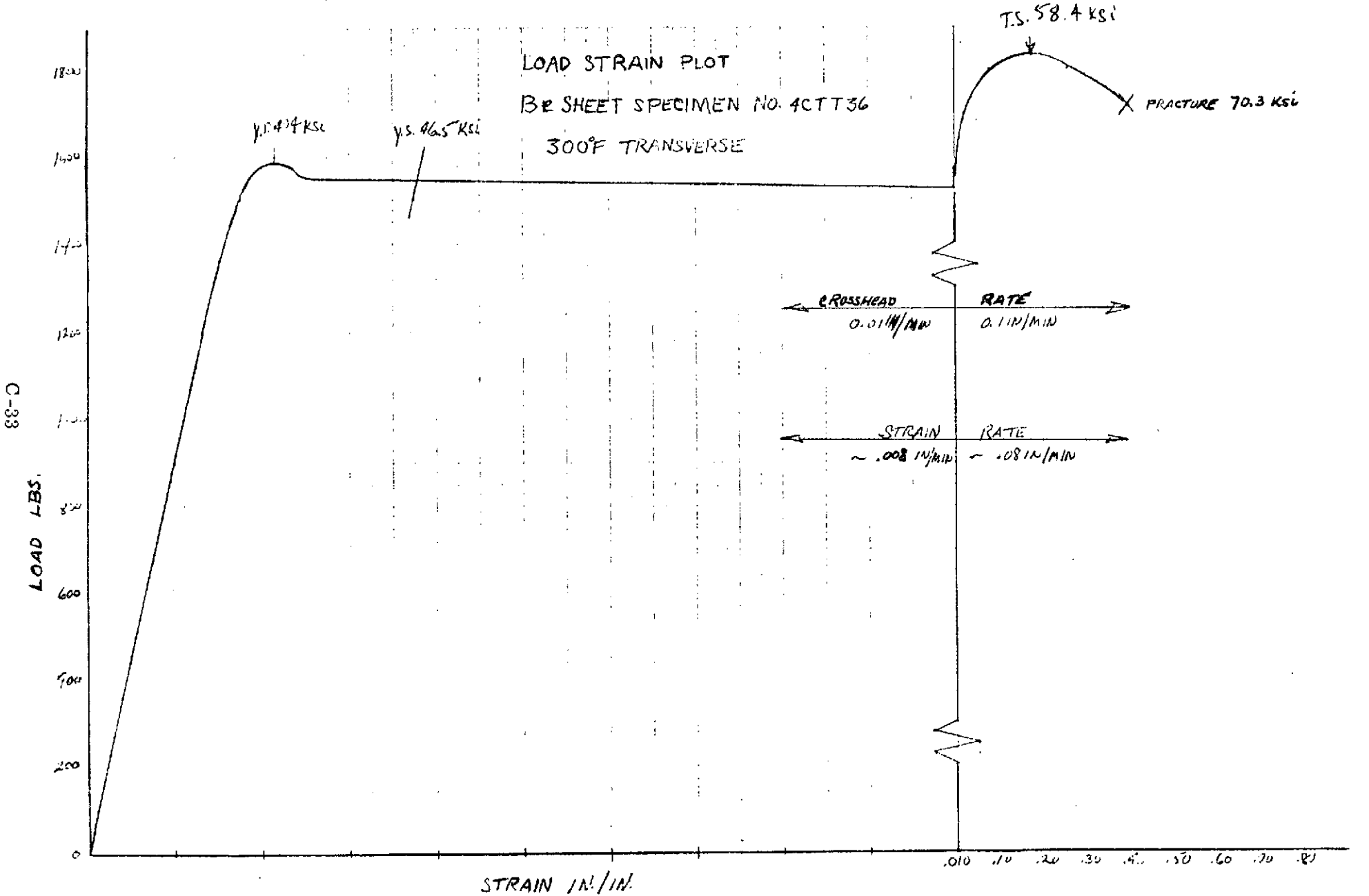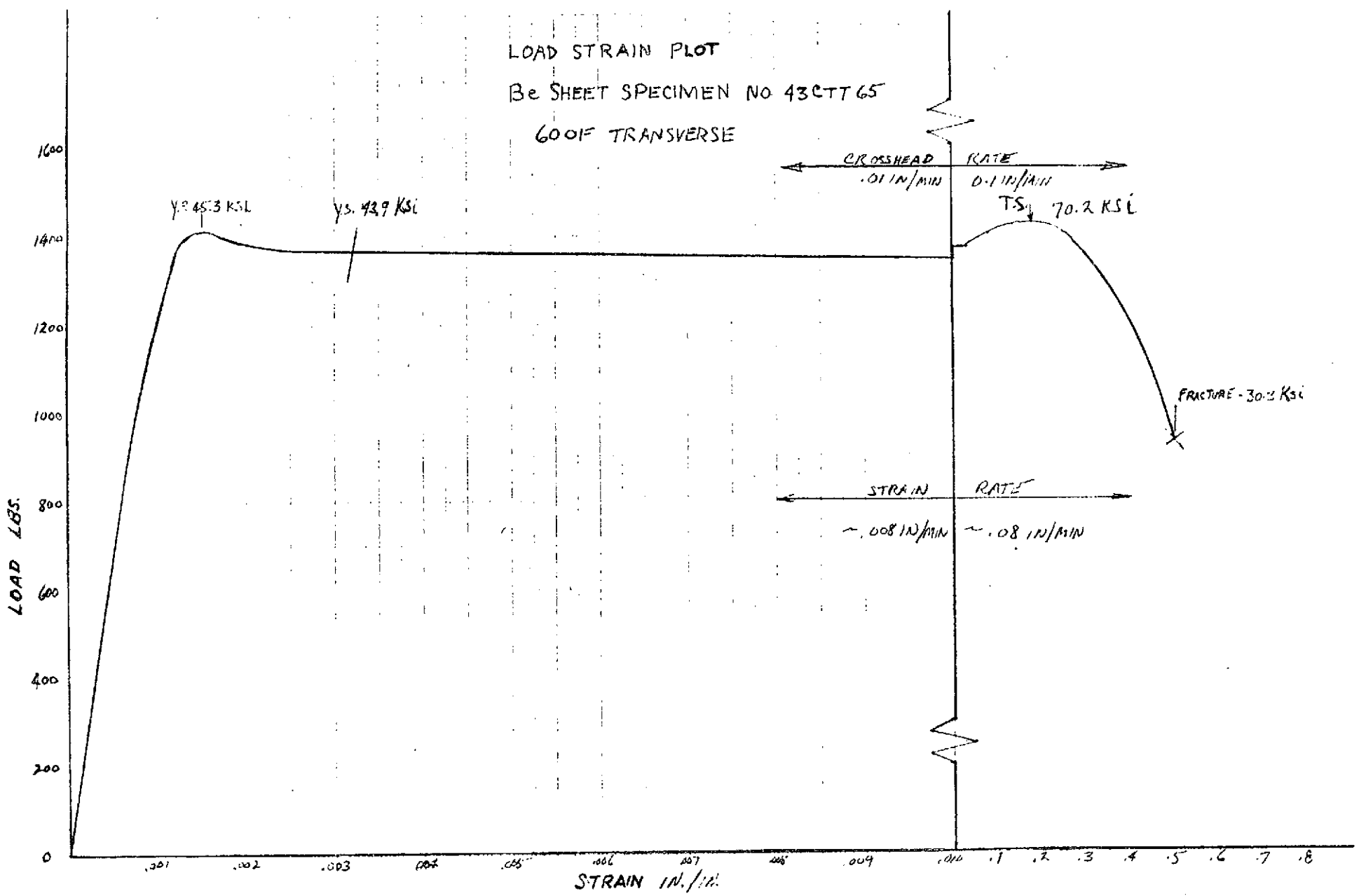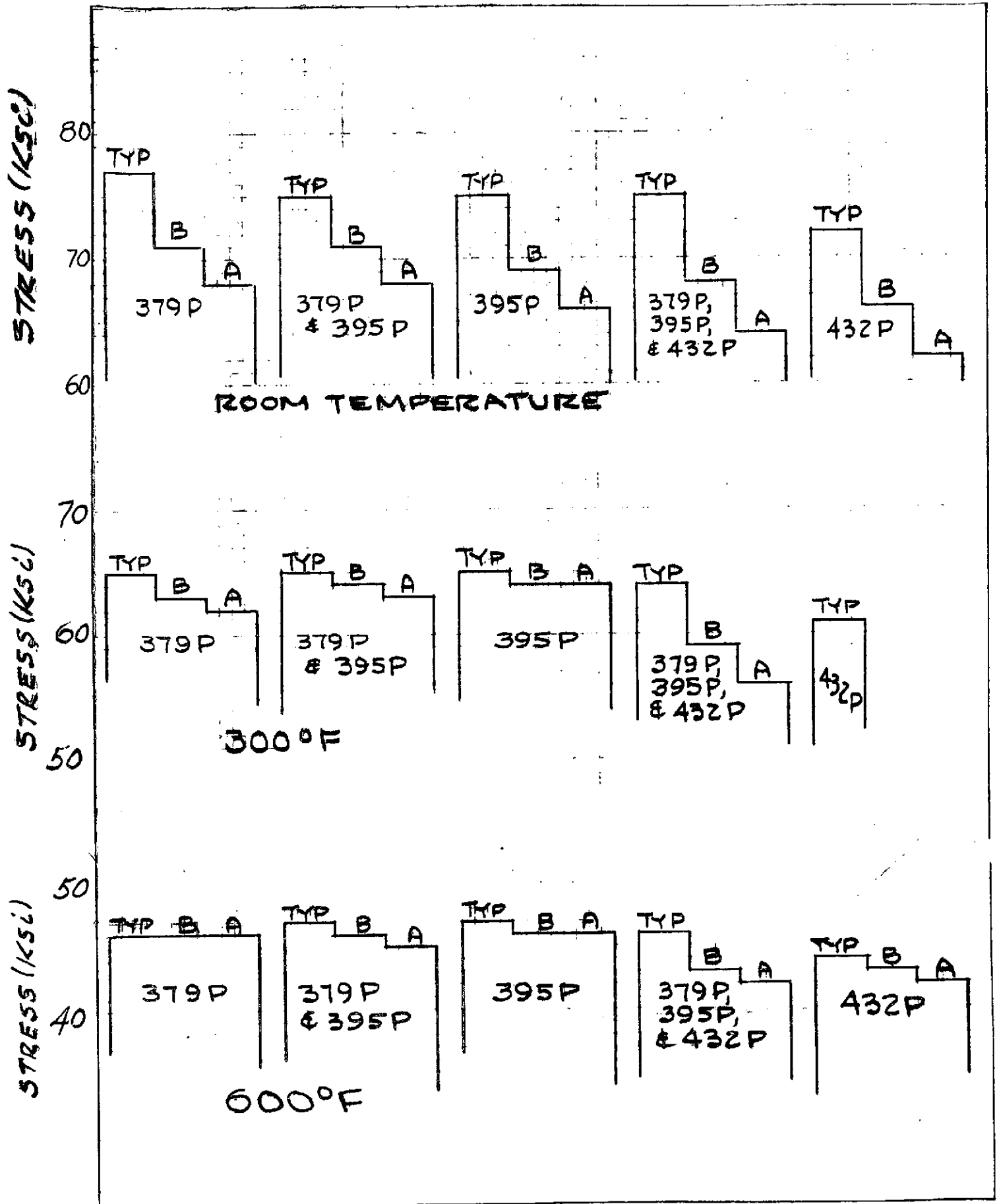
FIGURE 4 ULTIMATE TENSILE STRENGTH
LONGITUDINAL

J. Lang 5-31-72
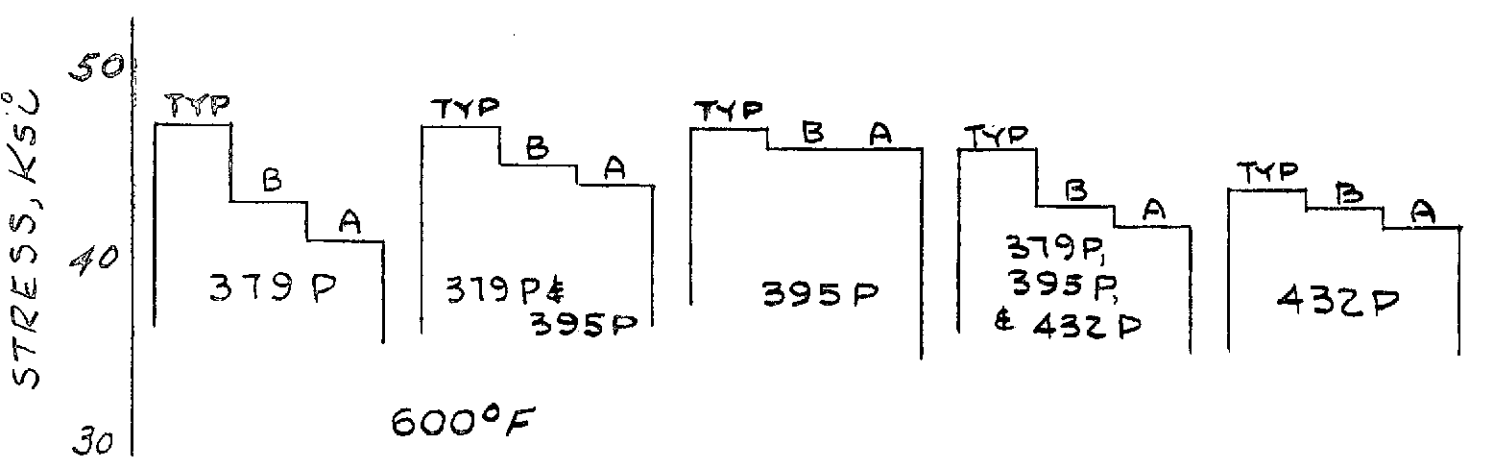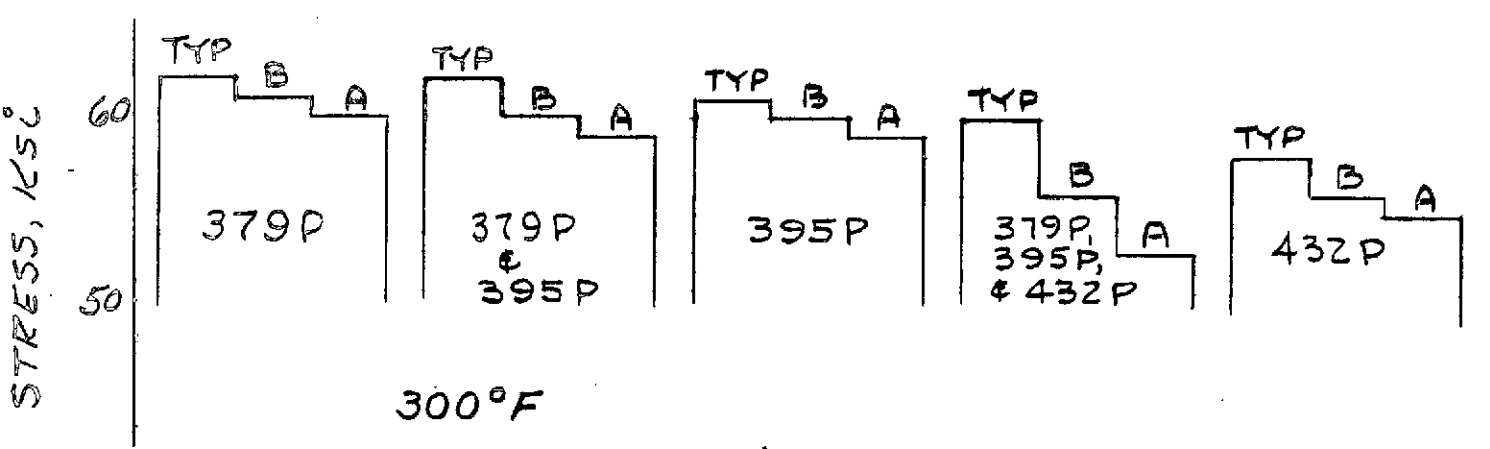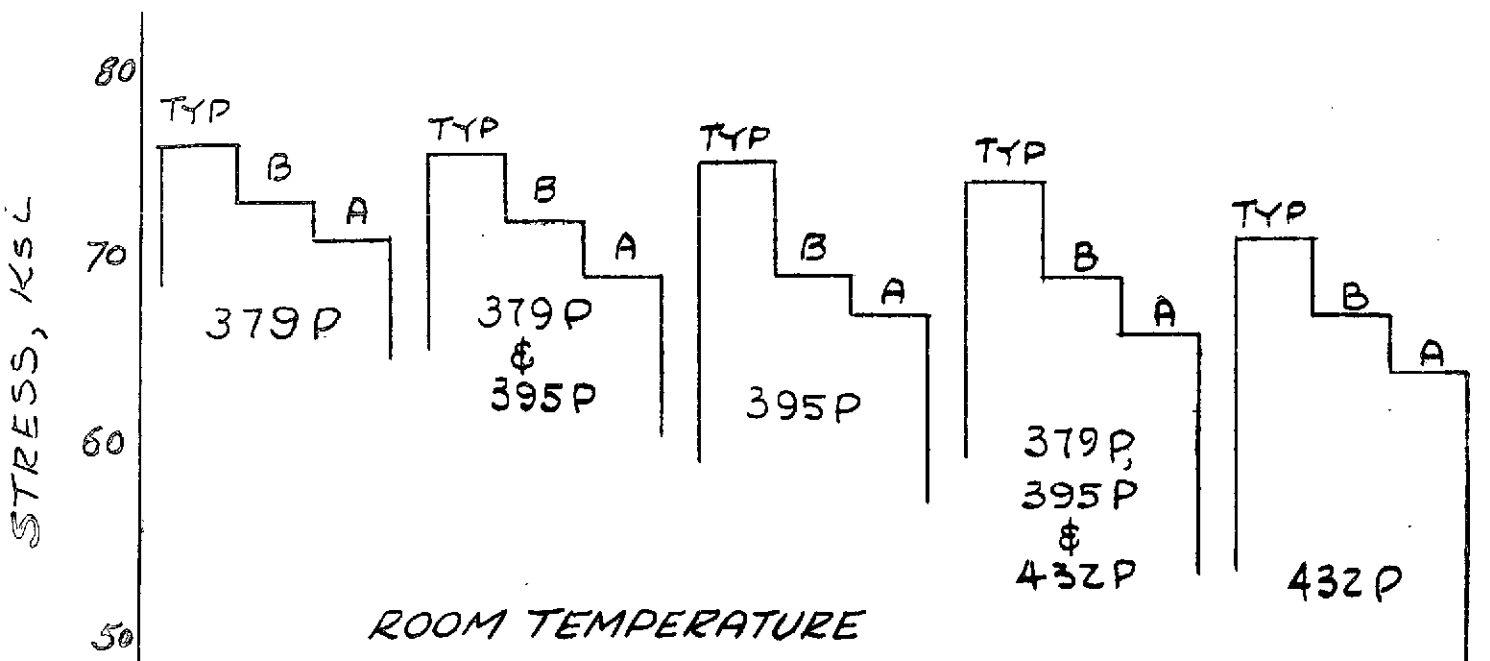
FIGURE 5 ULTIMATE TENSILE STRENGTH TRANSVERSE
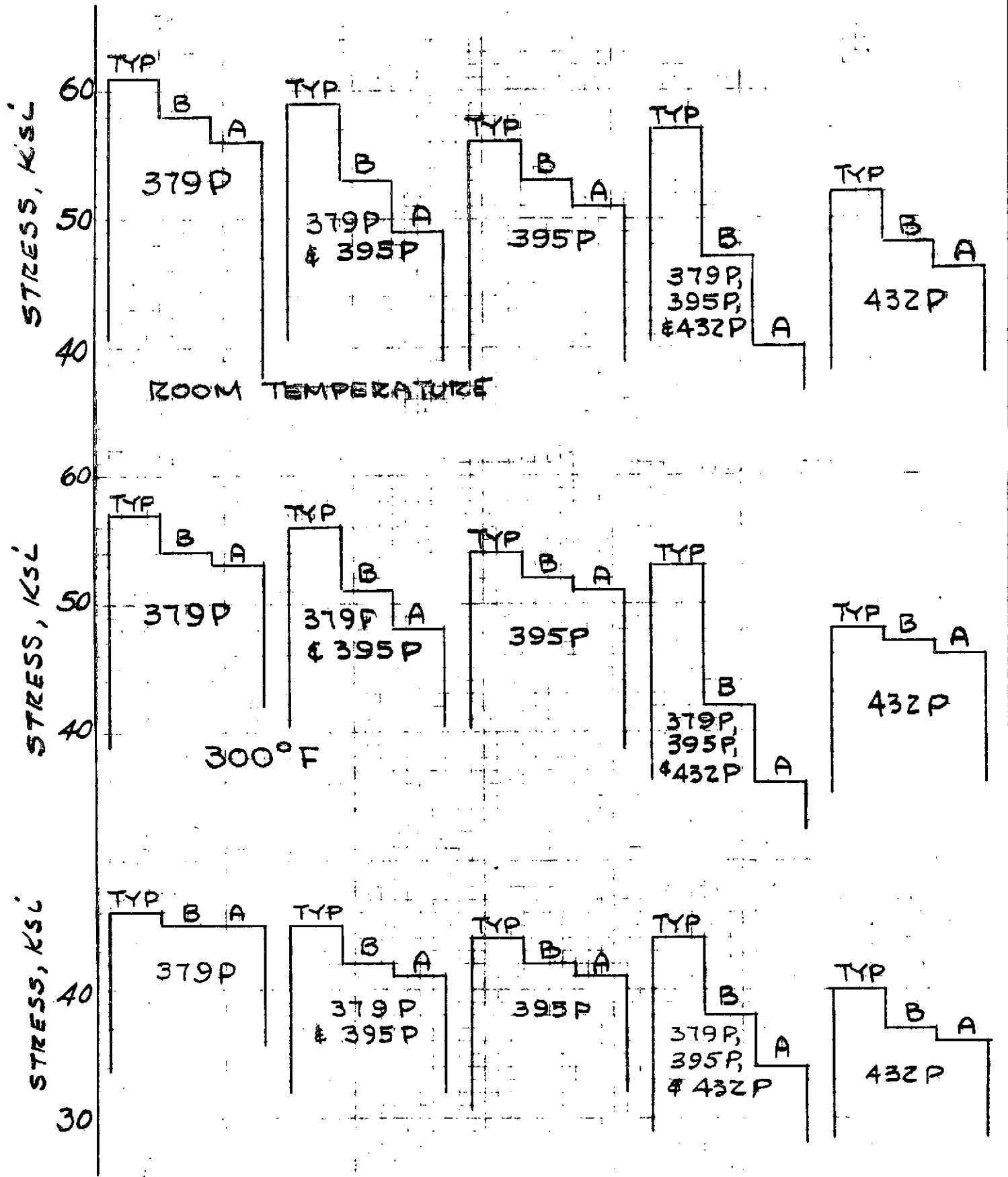
FIGURE 6 TENSILE YIELD STRENGTH
LONGITUDINAL

J. Lang 5-31-72
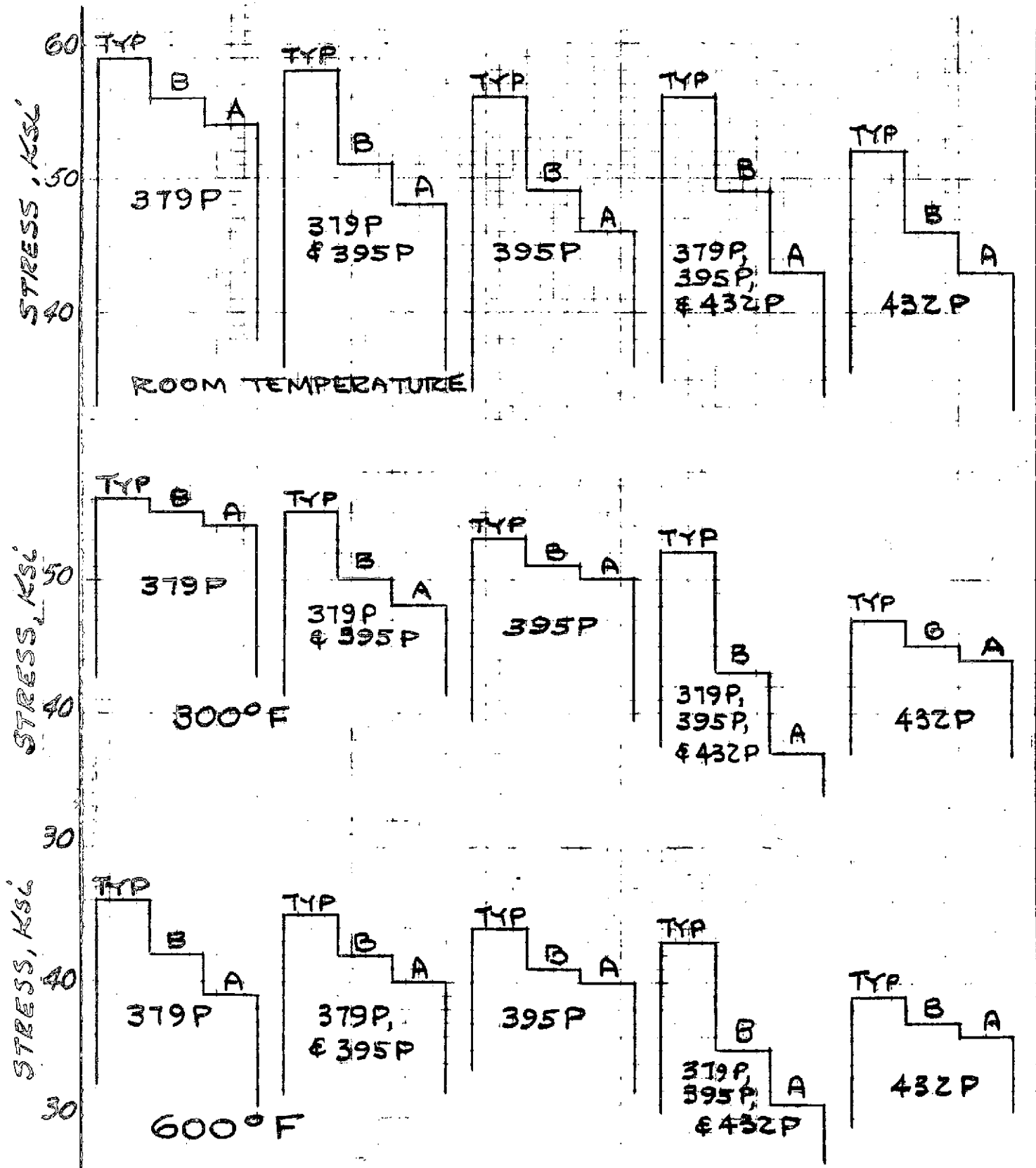
FIGURE 7   TENSILE YIELD STRENGTH
TRANSVERSE

Form LMSC 5588B-1

FIGURE θ· ULTIMATE TENSILE STRENGTH vs TEMPERATURE TRANSVERSE

STRESS, KSI

MEAN

B-BASIS

A-BASIS

TEMPERATURE, °F

FIGURE 10 TENSILE YIELD STRENGTH vs TEMPERATURE LONGITUDINAL

Figure 11: Tensile Yield Strength vs Temperature Transverse

STRESS, ksi

TEMPERATURE, °F

MEAN
B-BASIS
A-BASIS

FIGURE 12
LONGITUDINAL ELONGATION VS TEMPERATURE

Figure 13 — Transverse Elongation vs Temperature

ELONGATION, PERCENT IN 1-INCH

TEMPERATURE, °F

MEAN

B-BASIS

A-BASIS

FIGURE 14

$K = 26 \, Fe - Al/Fe$

FIGURE 15

379P — RT

395P

432P — 300°F

600°F

● : LONGITUDINAL
■ : TRANSVERSE

STRESS, KSI

70 — 60 — 50 — 40 — 30

1.98   1.99   2.00   2.01   2.02   2.03

$K = 26 \, Fe - Al/Fe$

FIGURE 16

BERYLLIUM SHEET
COMPRESSION
LOAD-STRAIN CURVES -- TYPICAL

FIGURE 17 COMPRESSIVE YIELD STRENGTH
LONGITUDINAL

J. Lang 5-31-72
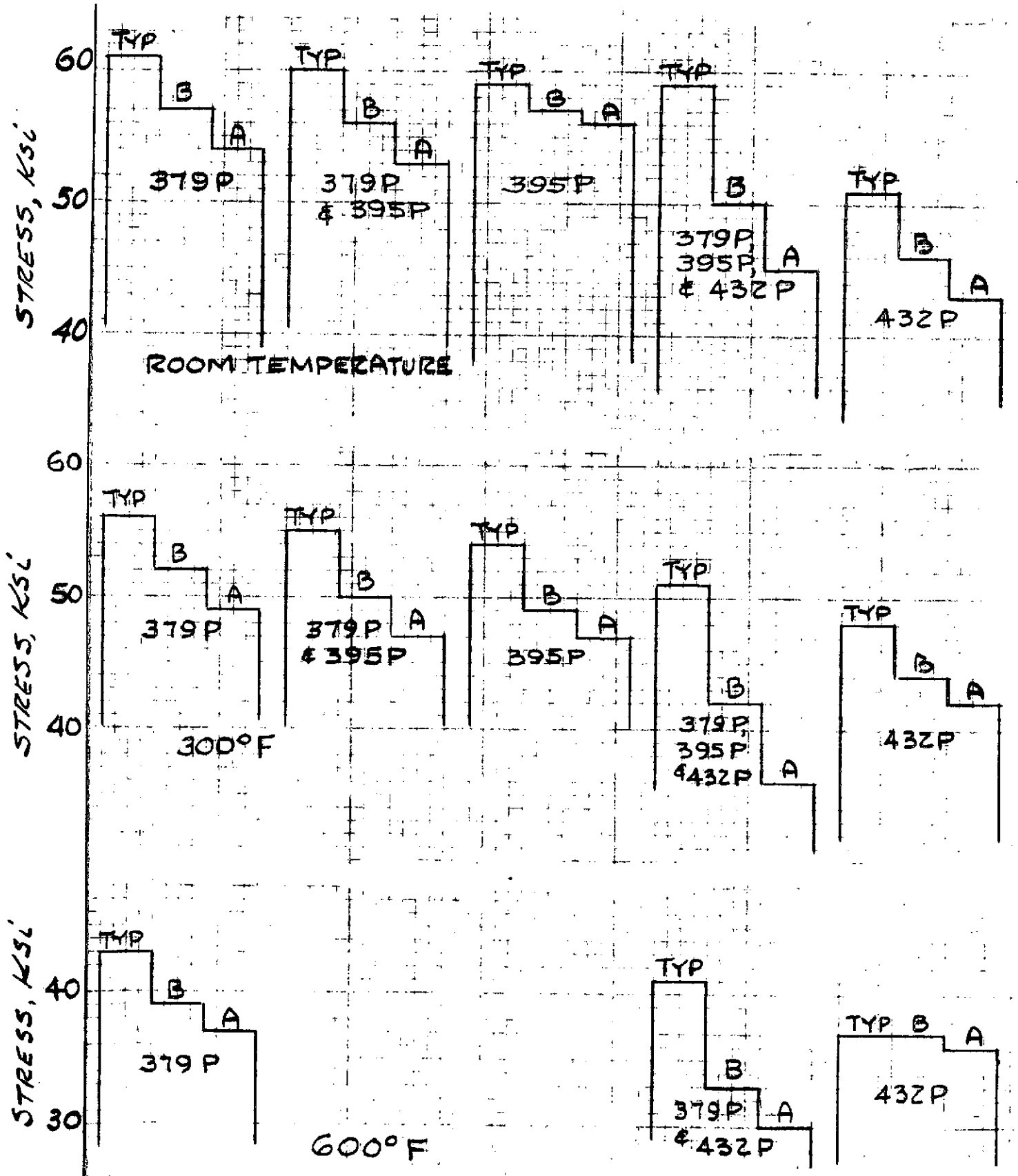
FIGURE 18 COMPRESSIVE YIELD STRENGTH
TRANSVERSE

C-3

Figure 19. Compressive Yield Strength vs Temperature Longitudinal

Prepared	NAME J. Lang	DATE 5·31·72	LOCKHEED MISSILES & SPACE COMPANY A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION	Page	TEMP.	PERM
Checked			TITLE FIGURE 19 COMPRESSIVE YIELD STRENGTH vs TEMPERATURE LONGITUDINAL	Model		
Approved				Report No.		

Form LMSC 5588B-1

C-50

FIGURE 20 COMPRESSIVE YIELD STRENGTH vs TEMPERATURE TRANSVERSE

STRESS, KSI

MEAN

B-BASIS

A-BASIS

TEMPERATURE, °F

Figure 21. Compressive Yield Strength (Typical)
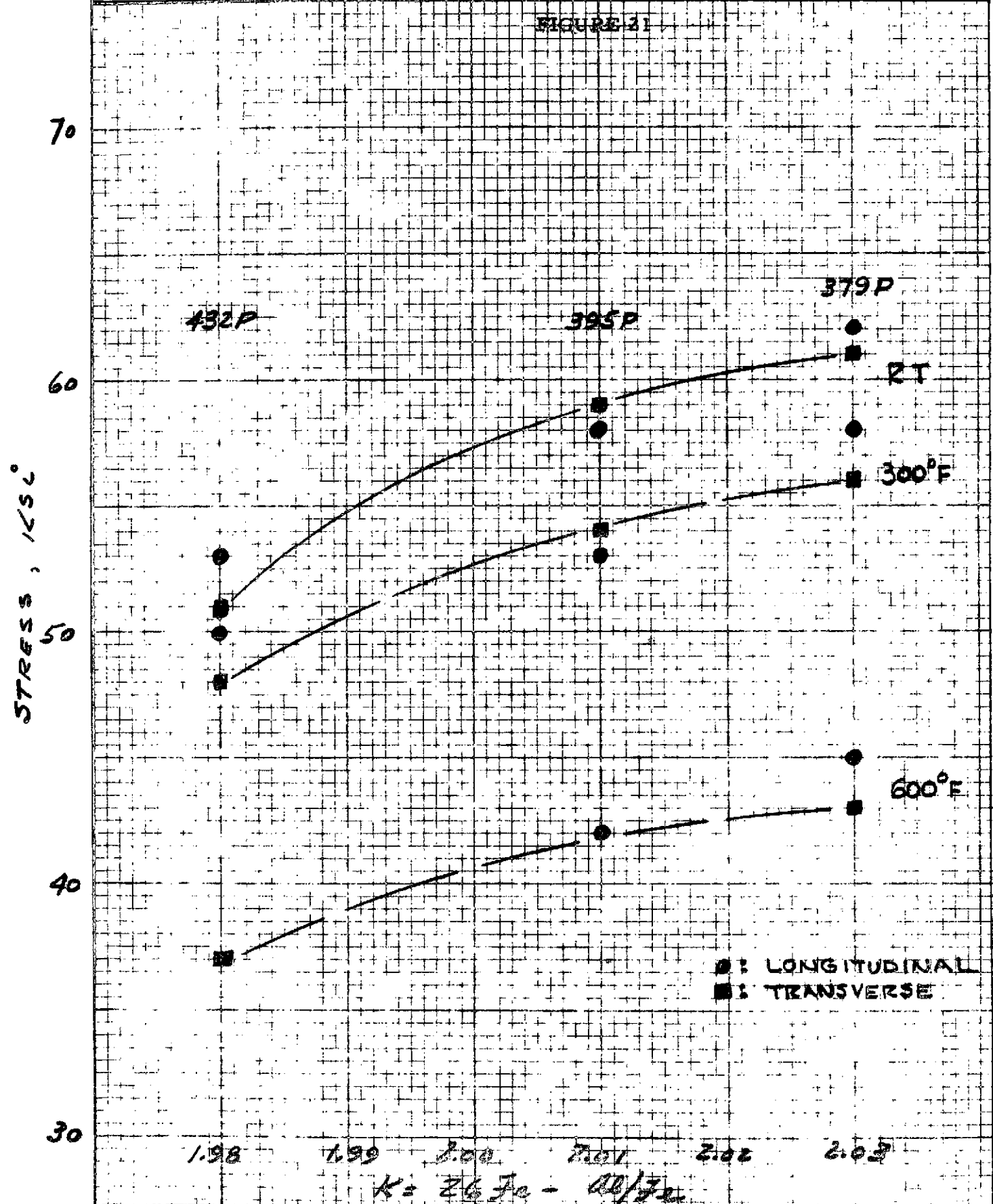
PERCENT CREEP-STRAIN AFTER 100 HOURS OF APPLIED STRESS AT TEMPERATURE

FIGURE 22

FIGURE 23

STANDARD FATIGUE
TESTING DATA
FOR BERYLLIUM SHEET
$K_t = 2.7$, $R = +.1$, $t = 0.120"$
STRESSES ARE MAXIMUM
FOR NET AREA.

E. WILLNER

CYCLES TO FAILURE

CONSTANT AMPLITUDE
FATIGUE DATA
FOR BERYLLIUM SHEET
$K_t = 2.7$, $R = +0.1$, $t = 0.140"$
STRESSES ARE MAXIMUM
FOR NET AREA

FIGURE 24

CYCLES TO FAILURE

FIGURE 25

STRAIN (1" = 0.010" STRAIN)
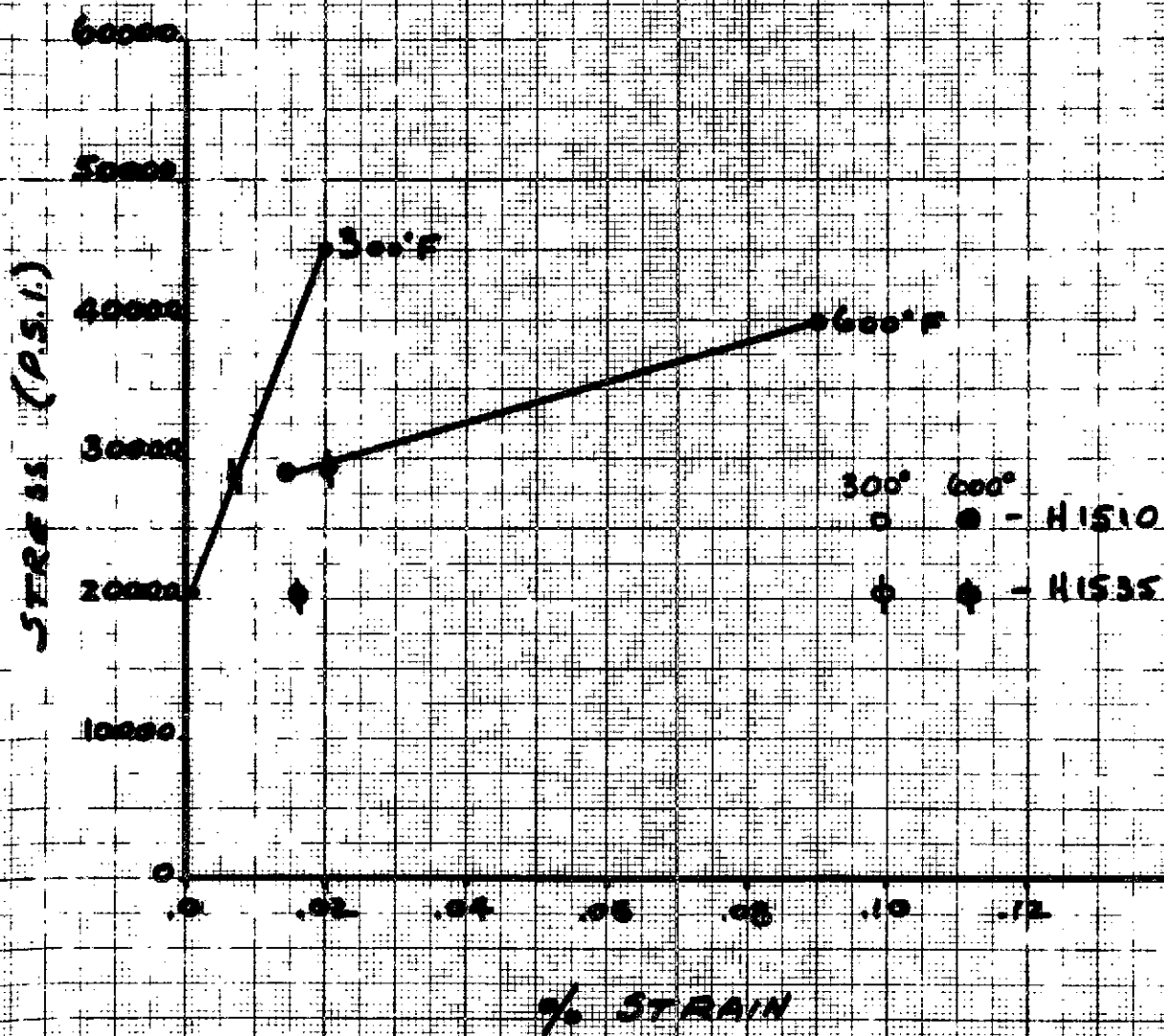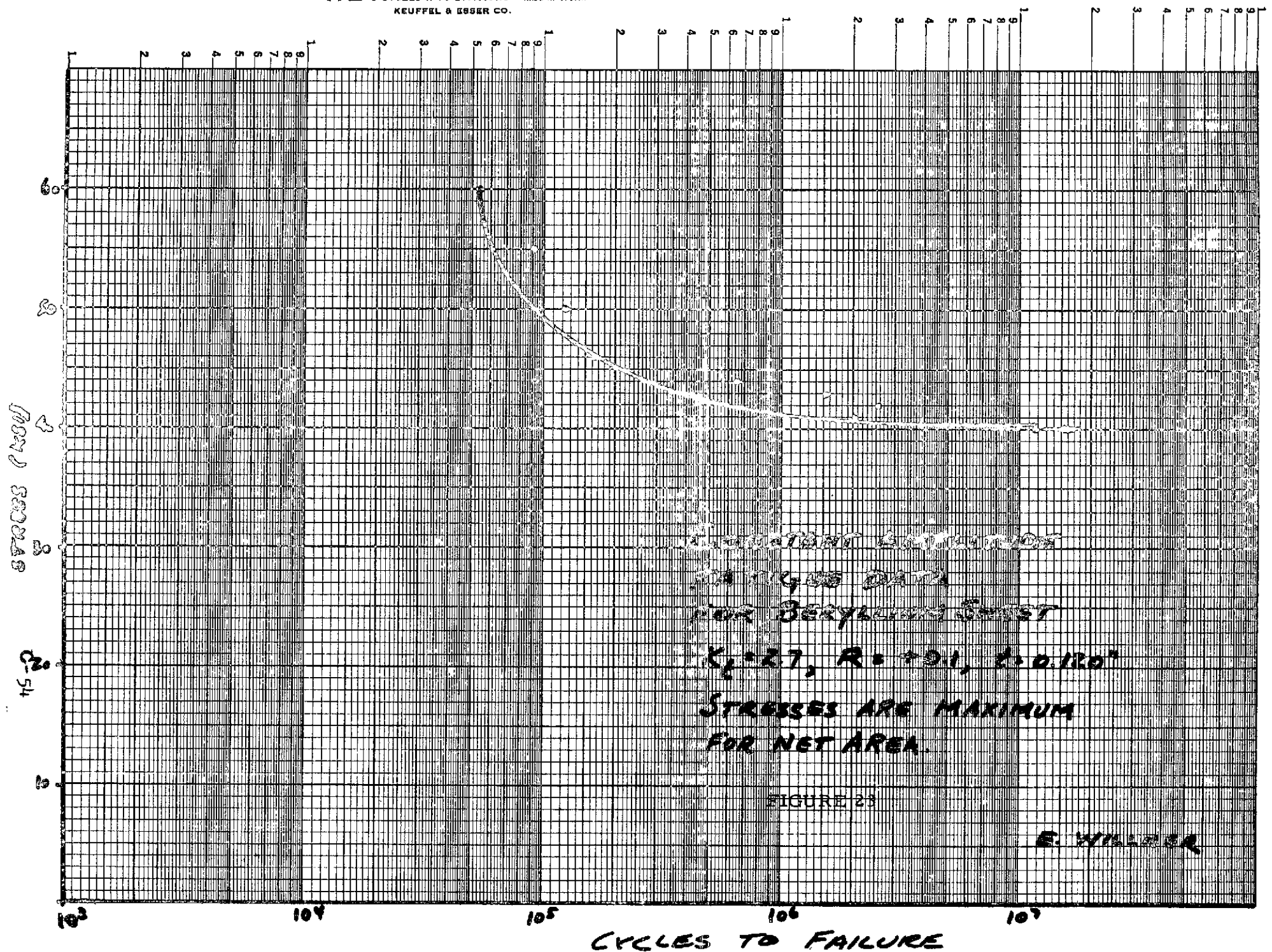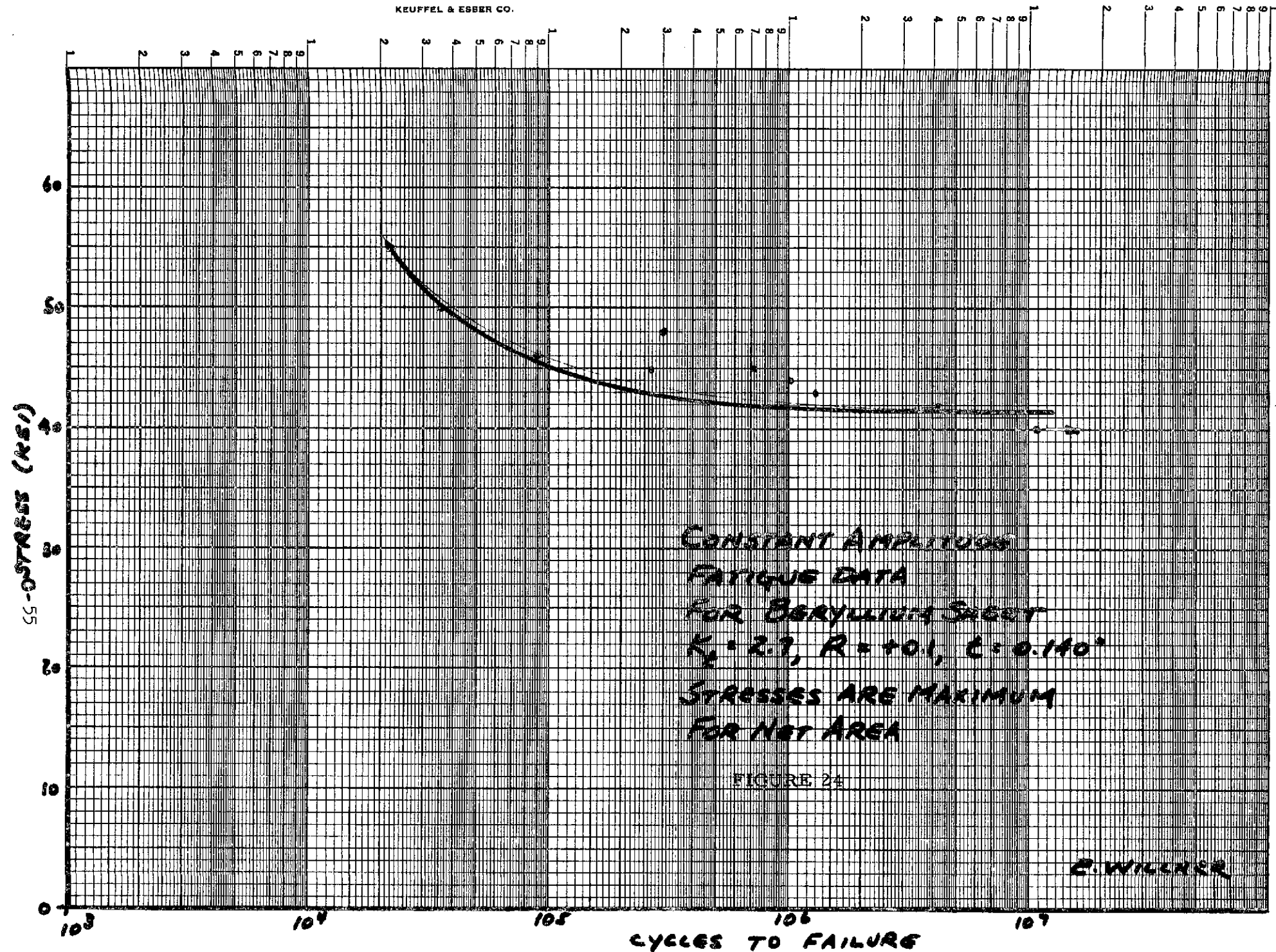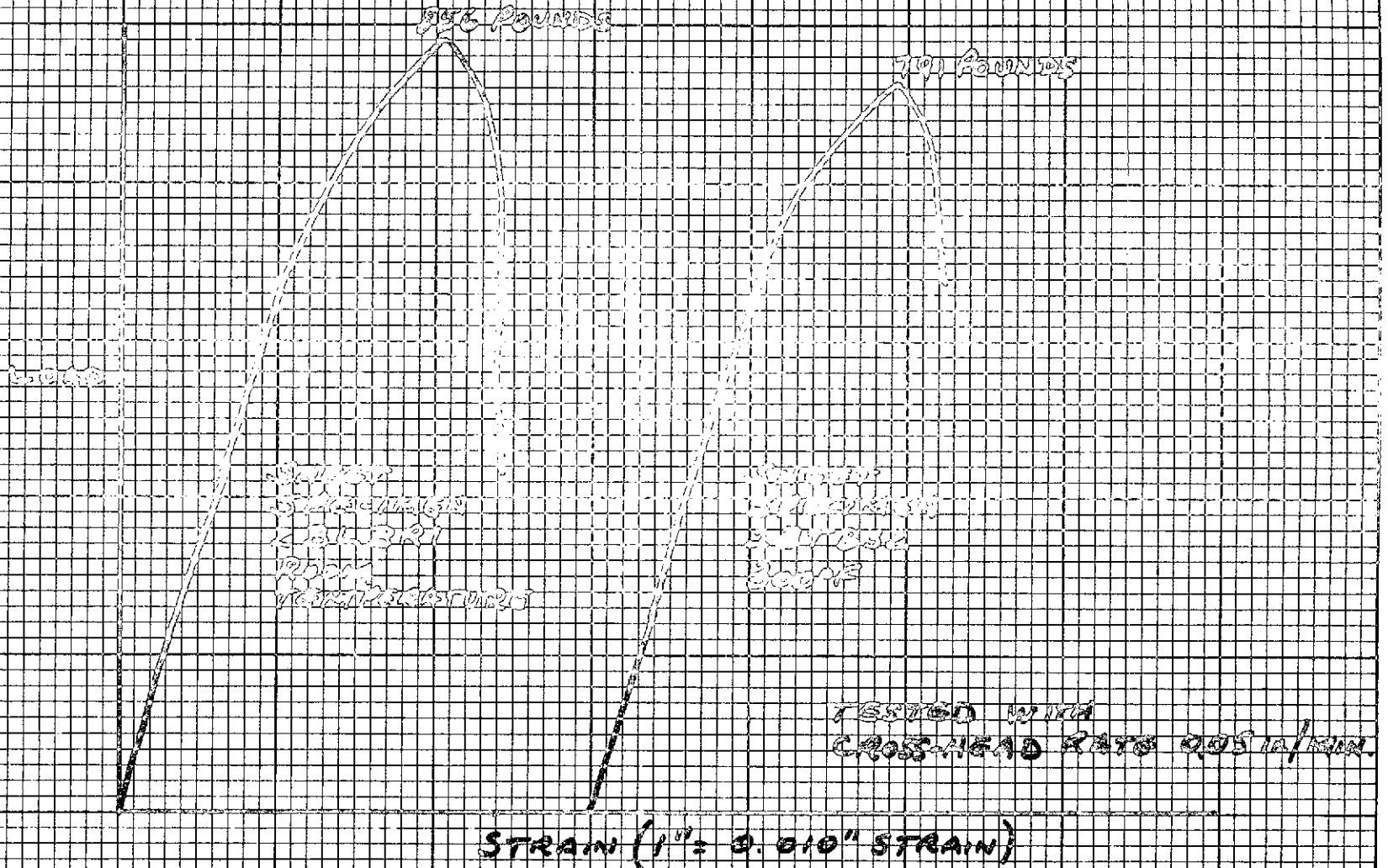
TYPICAL THREE POINT BENDING
BERYLLIUM LOAD - STRAIN CURVES AT R.T. AND 300°F

830 POUNDS

LOAD

SHEET
SPECIMEN
2CLB63
600°F

TESTED WITH
CROSS-HEAD RATE 0.05 IN./MIN

STRAIN (1" = 0.010" STRAIN)
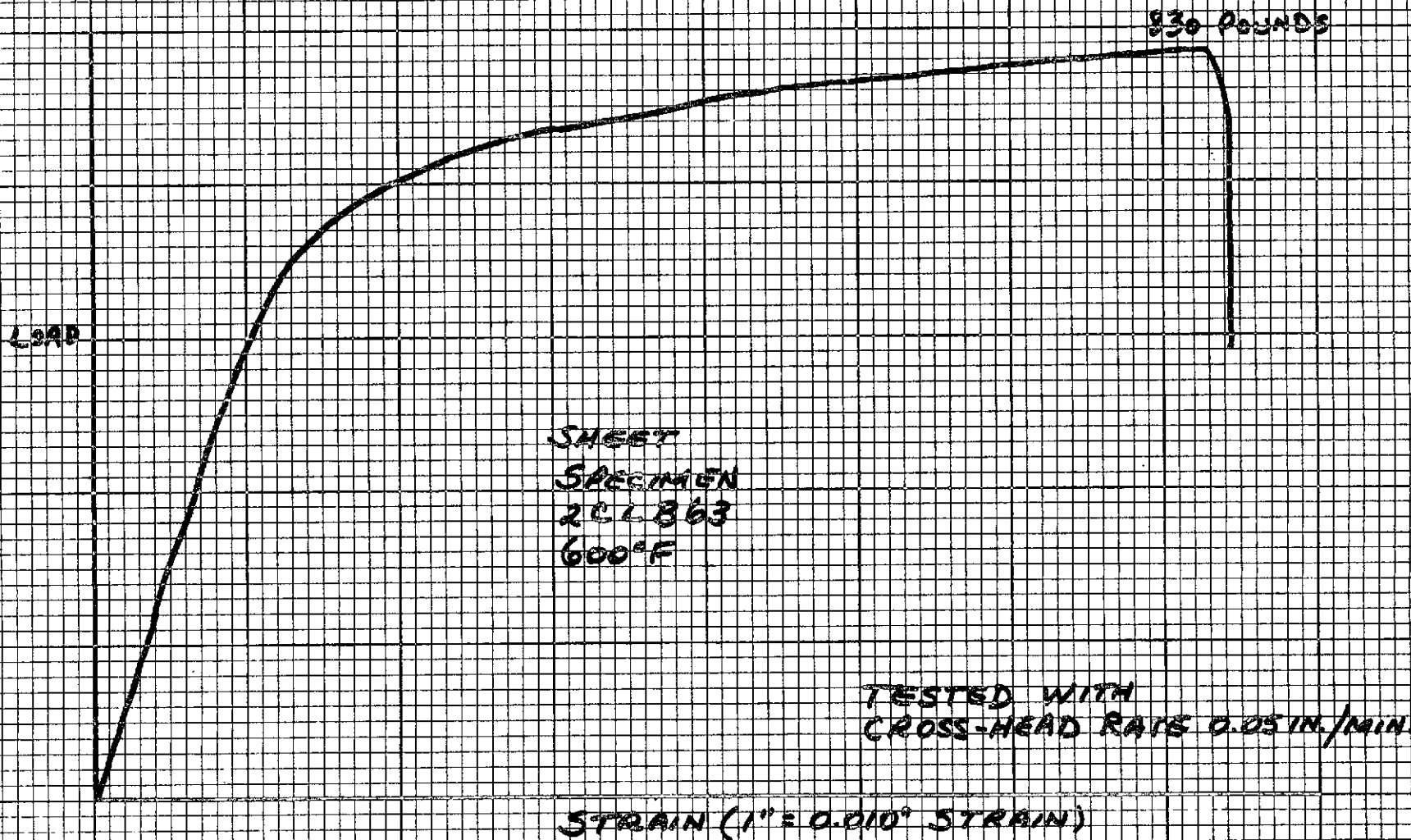
FIGURE 26   TYPICAL THREE POINT BENDING
BERYLLIUM LOAD-STRAIN CURVE AT 600°F

FIGURE 27

A9888

UTS=79 KSI
TYS=60 KSI
% = 23

LONGITUDINAL SPECIMEN   2BL BR1   x500
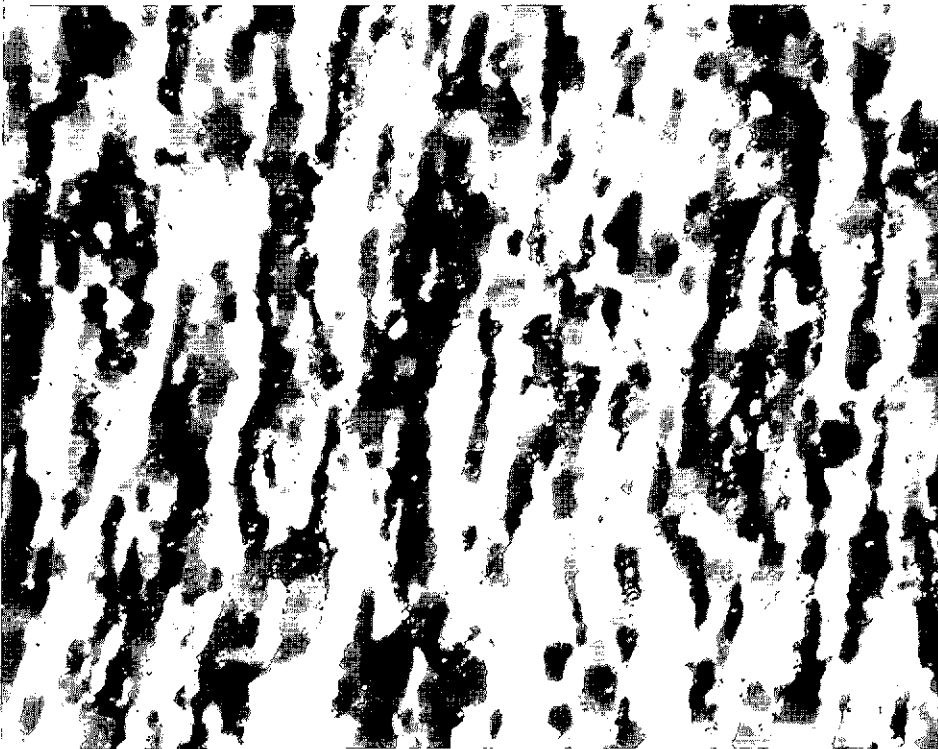
A9889

UTS=76 KSI
TYS=59 KSI
%= 22

TRANSVERSE SPECIMEN   2BTTR1   X500

FIGURE 28 METALLOGRAPHY
BERYLLIUM SHEET   H1514-379P
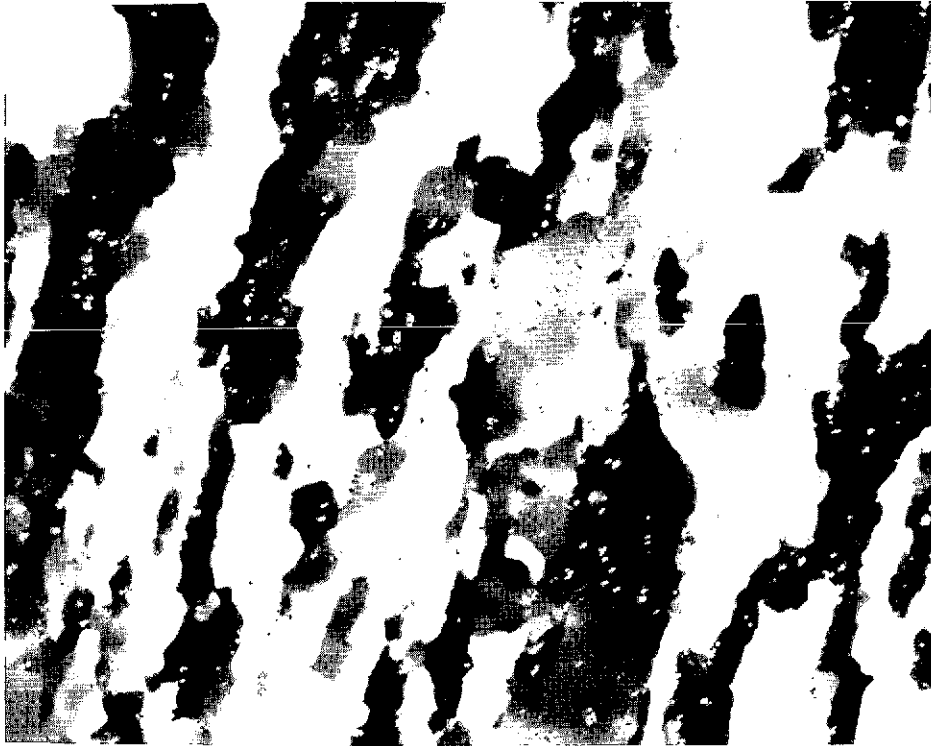
A9890

UTS=70 KSI
TYS=48 KSI

% = 8. 5

LONGITUDINAL SPECIMEN   4BLTR1   X 500
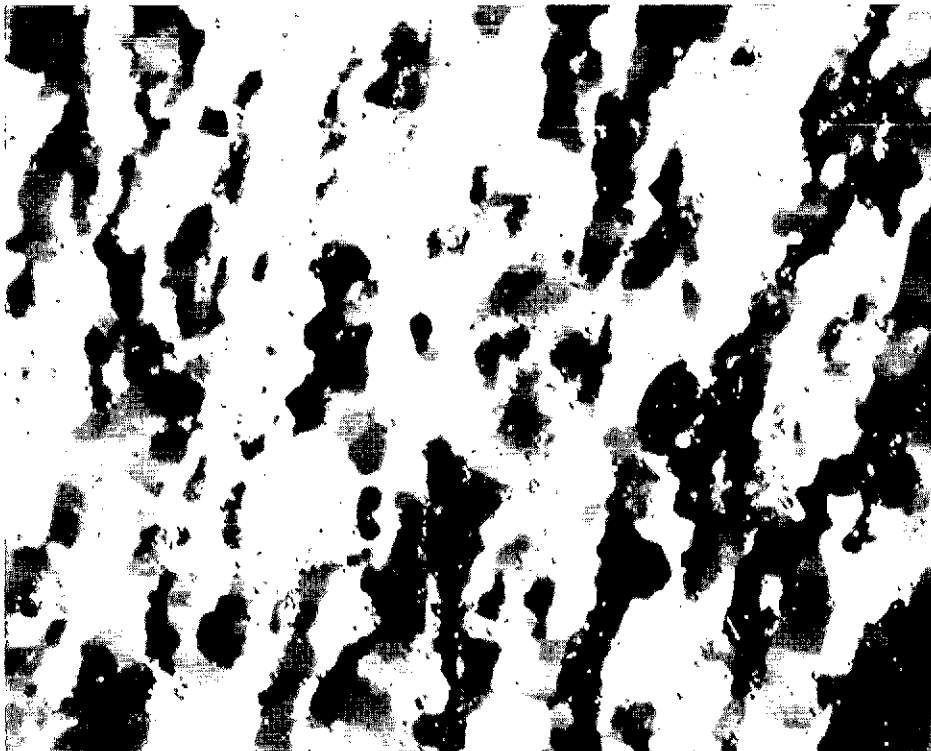
A9891

UTS=70
TYS=51
%E= 15

TRANSVERSE SPECIMEN   4BTTR1   X 500

FIGURE 29 METALLOGRAPHY
BERYLLIUM SHEET   H1532 - 432P
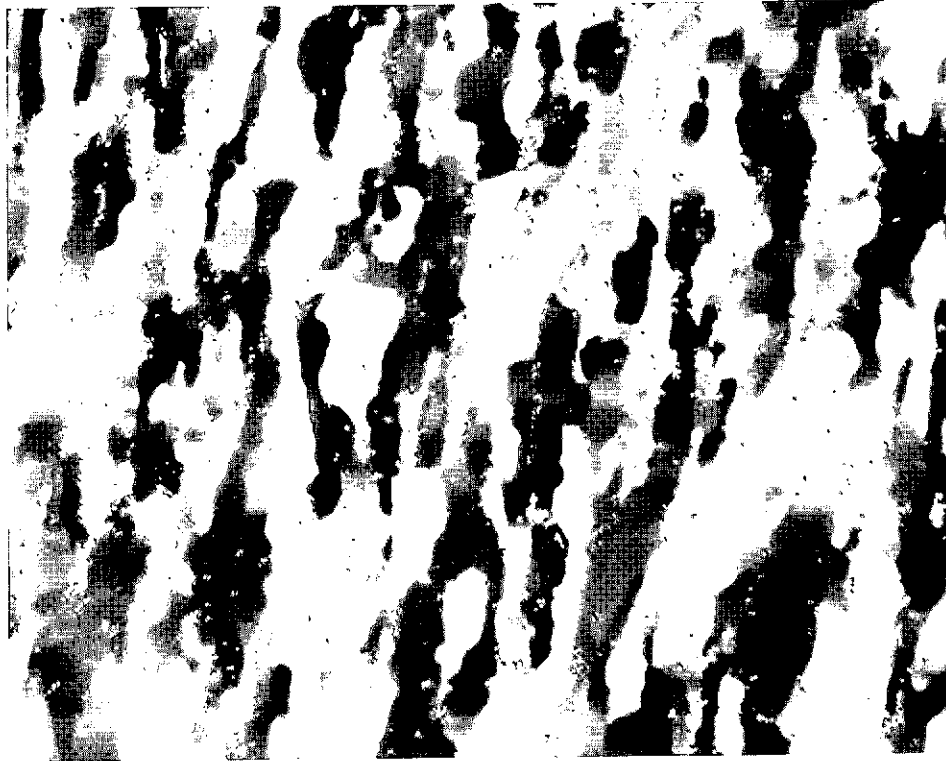
A9892

UTS=75 KSI
TYS=55 KSI
%E= 14

LONGITUDINAL SPECIMEN   43BLTR1   X 500
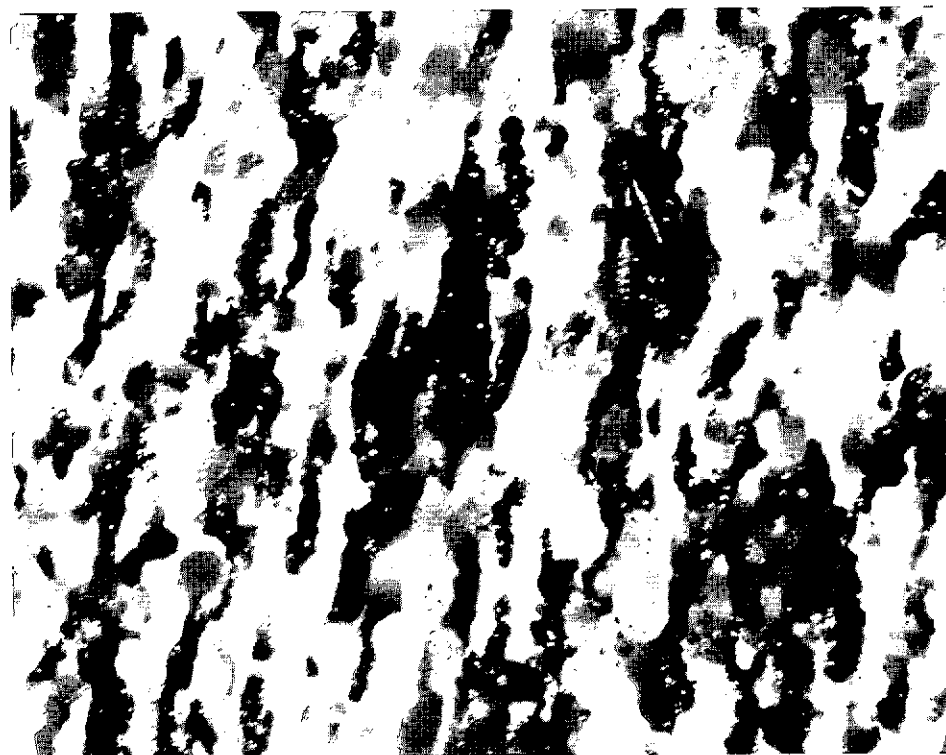
A9893

UTS=75 KSI
TYS=59 KSI
%E =18

TRANSVERSE SPECIMEN   43BTTR1   X 500

FIGURE 30   METALLOGRAPHY
BERYLLIUM SHEET   H1516-395P

Appendix D

EM B1-M2-1A

BERYLLIUM CROSS-ROLLED
SHEET DESIGN DATA

ENGINEERING MEMORANDUM

TITLE: 3.3 BERYLLIUM CROSS-ROLLED SHEET DESIGN DATA AT ROOM TEMPERATURE AND 600°F	EM NO: B1-M2-1A (Rev. A, 9-30-71) REF: DATE: 29 July 1971
AUTHORS: A. B. Burns, D. A. Rumbaugh, B. P. Van West	APPROVAL: ENGINEERING SYSTEM ENGRG A E Trapp

PROBLEM STATEMENT

Develop beryllium cross-rolled sheet design data for use on NASA/MSFC Contract NAS8-27739, "Design, Manufacture, Development, Test and Evaluation of Beryllium Structural Prototype Components for Space Shuttle." Data are required at room temperature and 600°F.

RESULTS

The following design curves were developed:

- Initial compression buckling (Figure 1)
- Initial shear buckling (Figure 2)
- Column buckling (Figure 3)
- Inter-rivet buckling (Figure 4)
- Compression post-buckling (Figure 5)
- Shear post-buckling (Figure 6)
- Crippling (Figures 7 - 9)

These design curves are based on the compressive stress-strain curves and tangent modulus curves shown in Figures 10 and 11. Evaluations of plasticity reduction factors as a function of stress are shown in Figures 12 and 13. Mechanical properties for beryllium cross-rolled sheet upon which the design curves have been based are summarized in the following table:

		R.T.		315°C (600°F)	
		N/mm^2	(psi)	N/mm^2	(psi)
F_{tu}		482	70,000	352	51,000
F_{ty}		345	50,000	276	40,000
F_{cy}		379	55,000	296	43,000
E		293,000	42.5×10^6	255,000	37.0×10^6
ν			0.0625		
e	% in 50 mm (2 in.)		5		

DISCUSSION

The mechanical properties and design curves cited above are based on specification minimum requirements and related data available at this time. These properties/design curves will be reviewed and updated as required upon completion of the materials characteristics evaluation task. The procedures cited in Ref. 1 were used to develop the attached curves, with

some exceptions. The compression post-buckling curve (Figure 5) represents a curve drawn through tests of square tubes and V-groove supported plates, which are summarized in Ref. 2. Post-buckling test of beryllium plates reported in Ref. 1 are conservatively predicted with the use of this curve. The curves for shear post-buckling (Figure 6) are taken from Ref. 3. These curves are based on tests documented in this report in combination with tests of shear webs reported in Ref. 1. The nondimensional crippling curves presented in Figure 9 are also taken from Ref. 3 where they are well documented with tests. These curves are recommended for crippling design of individual sections; the crippling curves shown in Figures 7 and 8 are recommended for composite skin-stringer sections. The cutoff stresses shown in Figures 1 - 4, 7 and 8 have been conservatively set equal to the compressive yield stress in the absence of test data to support higher values which are usually specified for more conventional materials.

REFERENCES

1. Crawford, R. F. and Burns, A. B., "Strength, Efficiency and Design Data for Beryllium Structures", ASD-TR-61-692, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, February 1962.

2. Mayers, J., Nelson, E. and Smith, L. B., "Maximum Strength Analysis of Post-buckled Rectangular Plates", SUDAER No. 215, Department of Aeronautics and Astronautics, Stanford University, Stanford, California, December 1964.

3. Finn, J. M., Koch, L. C., and Muehlberger, D. E., "Design, Fabrication, and Test of an Aerospace Plane Beryllium Wing-Box" AFFDL-TR-67-38, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, March 1967.

FIG. 1: INITIAL COMPRESSION BUCKLING CURVES
BERYLLIUM CROSS-ROLLED SHEET
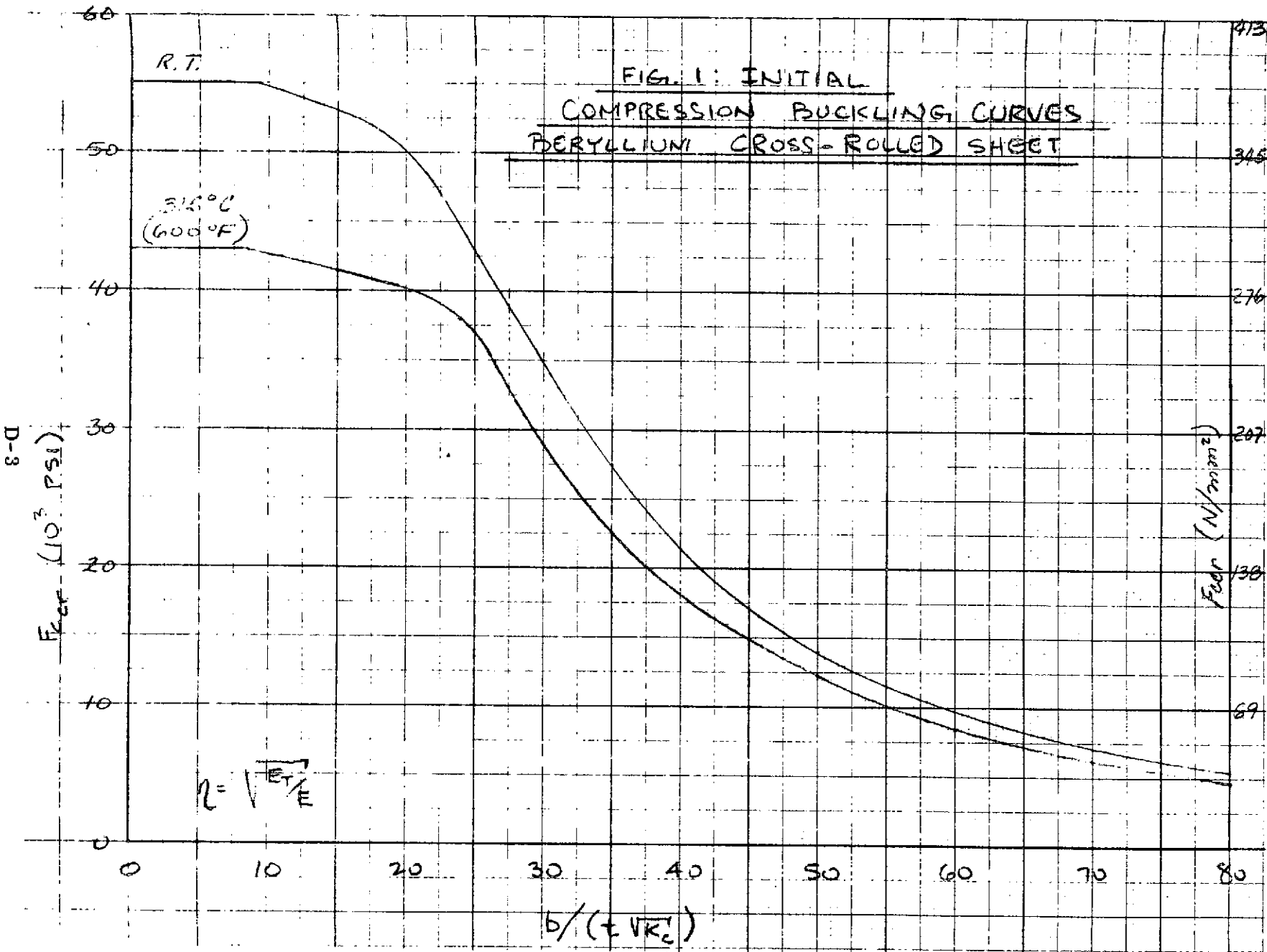
FIG. 2 : INITIAL SHEAR BUCKLING CURVES, BERYLLIUM CROSS-ROLLED SHEET
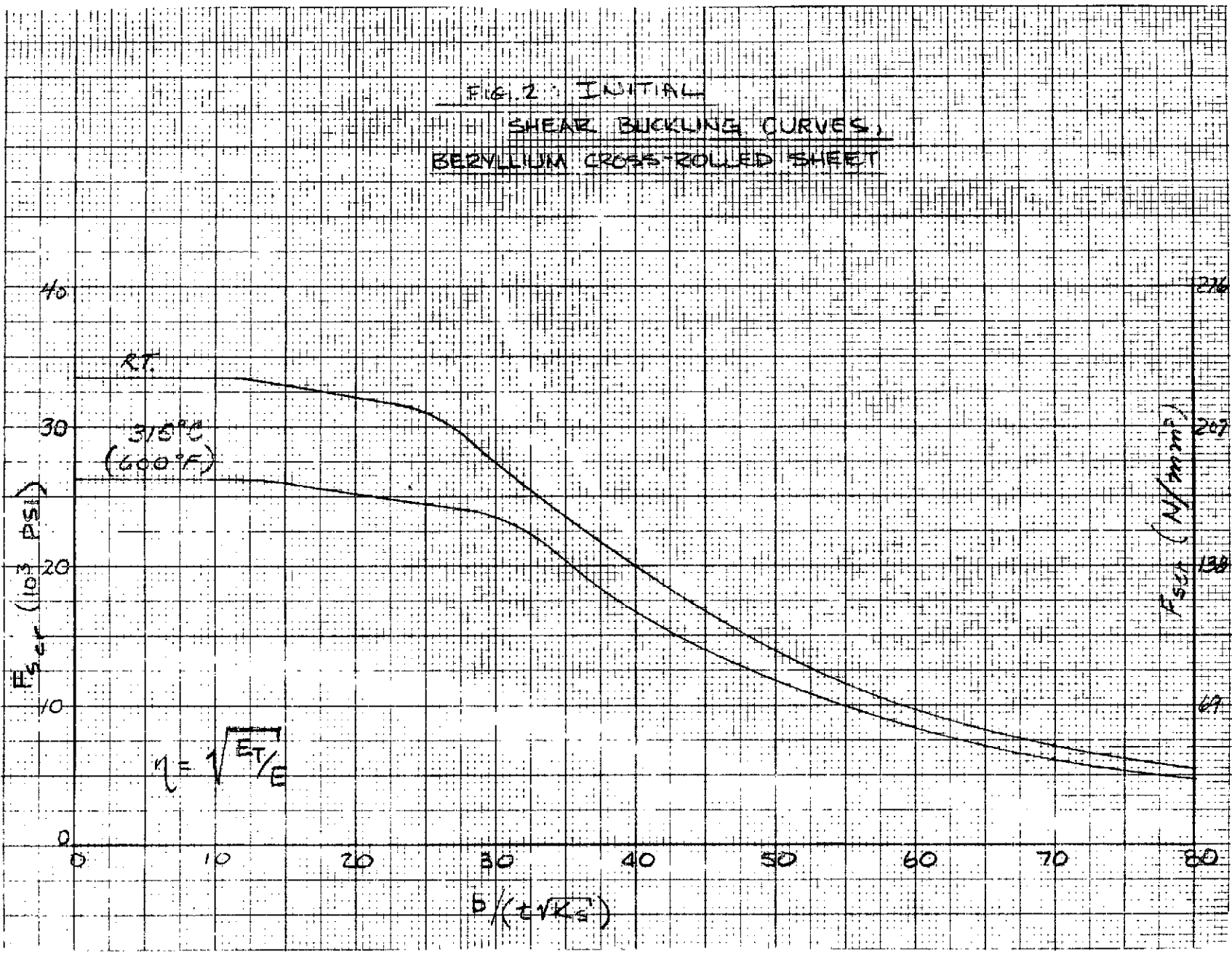
$$\eta = \sqrt{\frac{E_T}{E}}$$

FIG. 3 : COLUMN BUCKLING CURVES, BERYLLIUM CROSS-ROLLED SHEET

FIG. 4:
INTER-RIVET BUCKLING CURVES,
BERYLLIUM CROSS-ROLLED SHEET
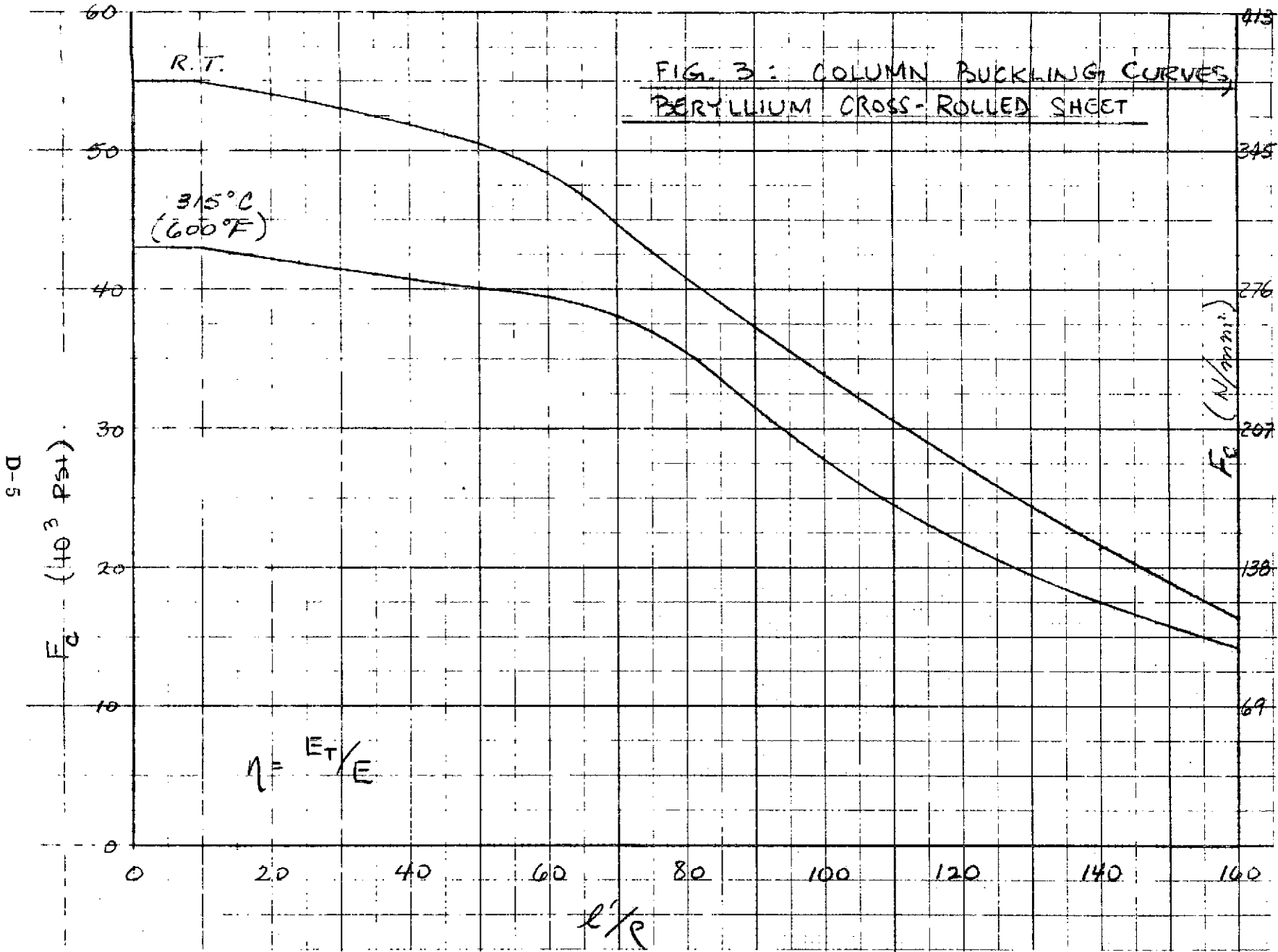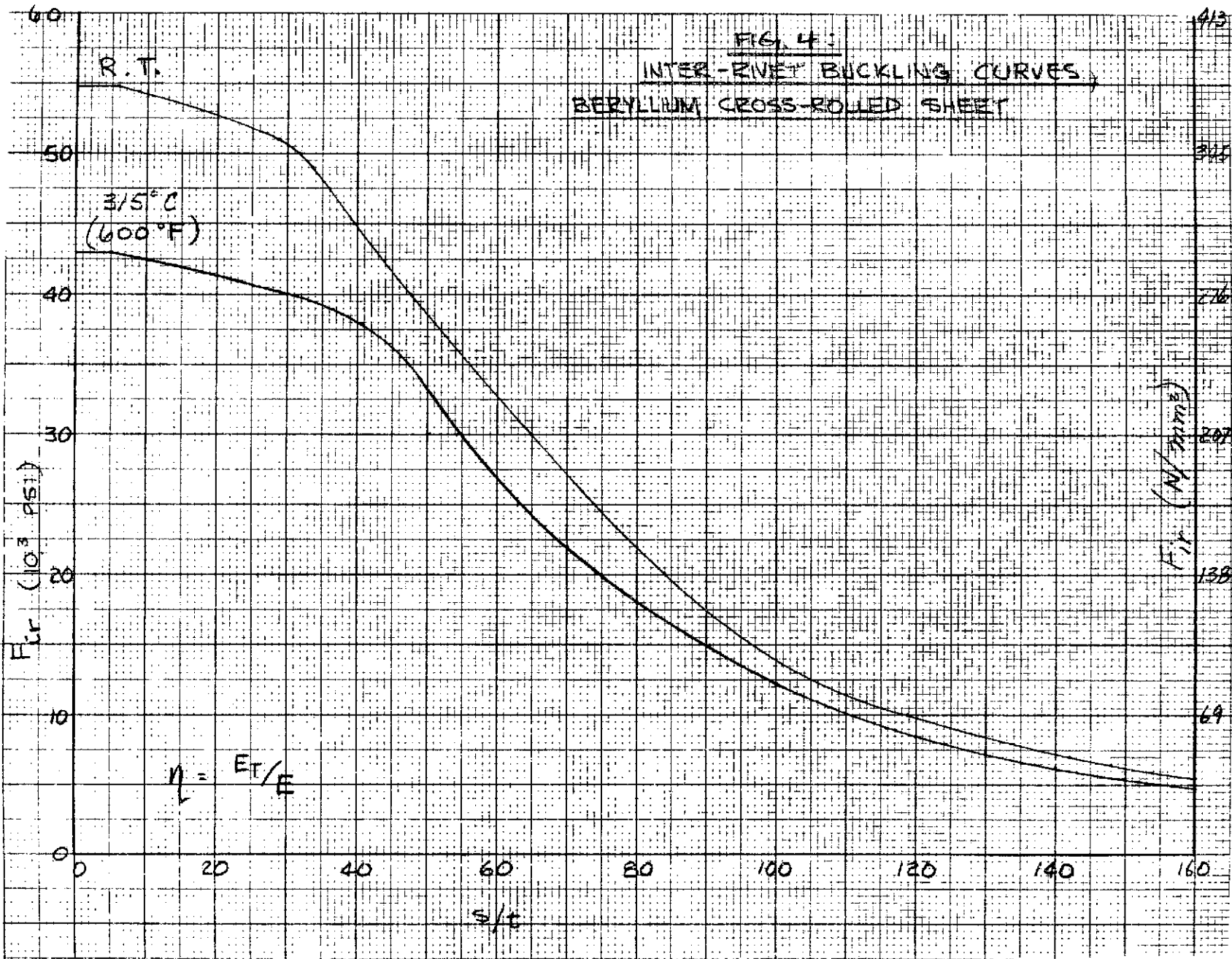
FIG. 5: NON-DIMENSIONAL
COMPRESSION POST-BUCKLING
CURVE FOR BERYLLIUM
CROSS-ROLLED SHEET

FIG. 6: SHEAR POST-BUCKLING CURVES FOR BERYLLIUM CROSS-ROLLED SHEET

CURVED ELEMENT — ONE EDGE FREE

CURVED ELEMENT — NO EDGE FREE

FLAT ELEMENT — ONE EDGE FREE

FLAT ELEMENT — NO EDGE FREE

FIG. 7 : CRIPPLING CURVES,
BERYLLIUM CROSS-ROLLED SHEET
ROOM TEMPERATURE

F_{cc} (10^3 PSI)

F_{cc} (N/mm^2)

b/t

R/t

FIG. 8: CRIPPLING CURVES
BERYLLIUM CROSS-ROLLED SHEET
3/5" ℓ (600°F)

FIG. 9: NON-DIMENSIONAL CRIPPLING CURVES FOR BERYLLIUM CROSS-ROLLED SHEET

FIG. 10: BERYLLIUM CROSS-
ROLLED SHEET COMPRESSIVE
STRESS-STRAIN CURVE
(ESTIMATED) t = 0.100 in.
ROOM TEMPERATURE

345

276

207

138

69

E_T

$E = 293,000 \text{ N/mm}^2$ (42.5×10^6 PSI)

COMPRESSIVE STRESS (N/mm²)

COMPRESSIVE STRESS (10³ PSI)

TANGENT MODULUS (N/mm²)
68,900   137,900   206,800   275,800   344,700

STRAIN (0.001 IN./IN.)
TANGENT MODULUS (10⁷ PSI)
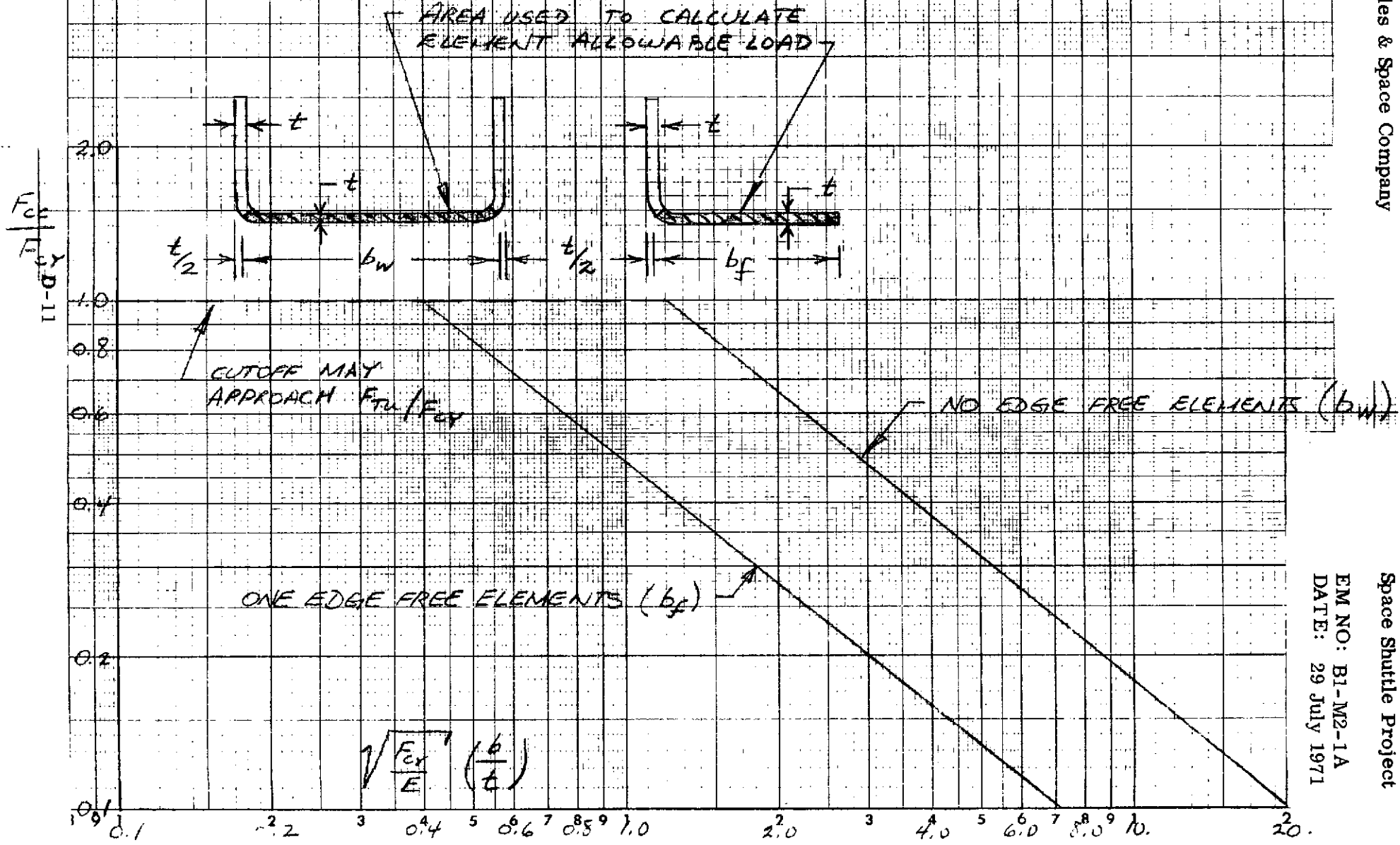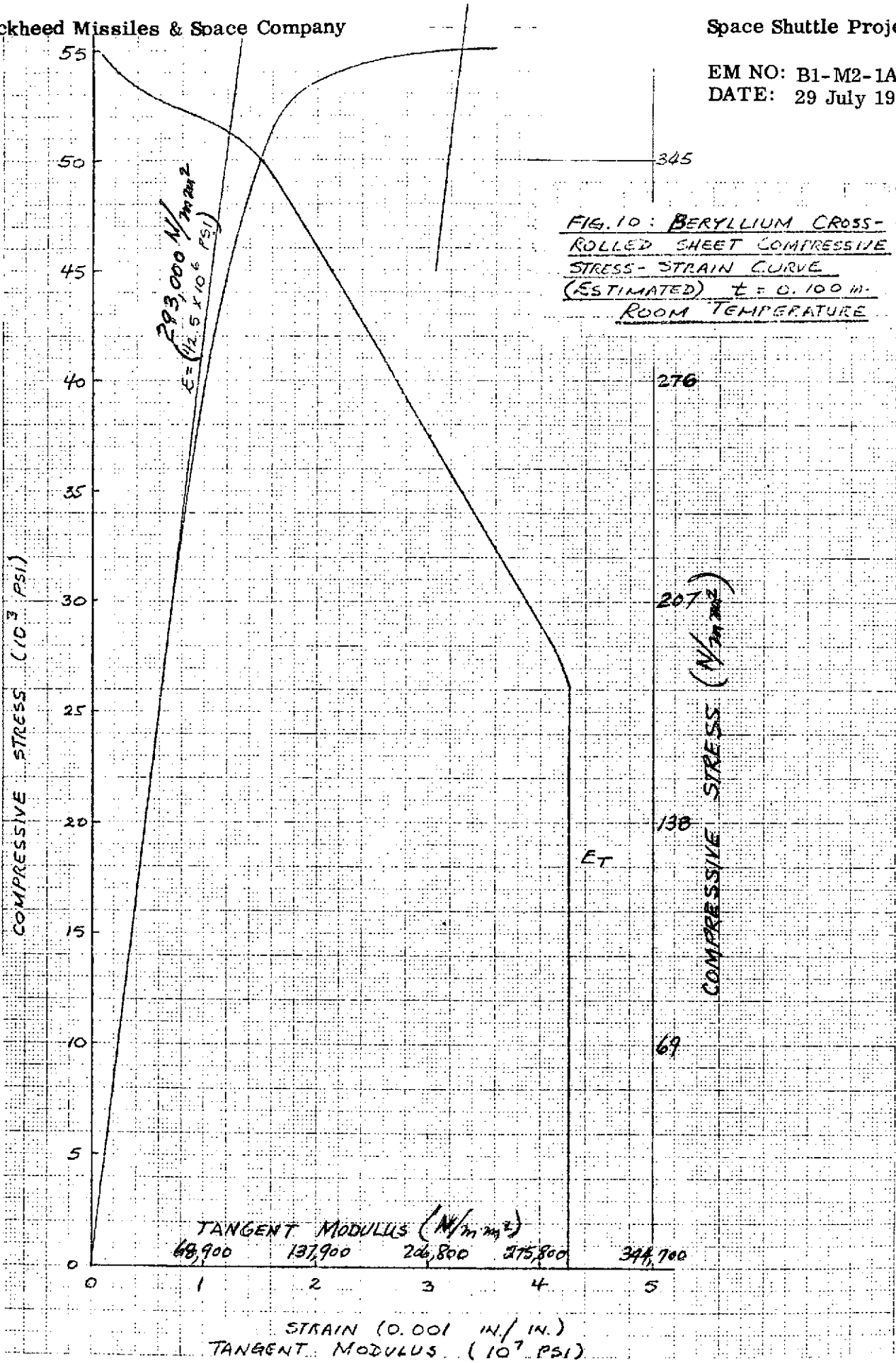
FIG. 11: BERYLLIUM CROSS-ROLLED SHEET
COMPRESSIVE STRESS-STRAIN CURVE
(ESTIMATED) $\dot{\epsilon} = 0.100$ IN.
315°C (600°F)
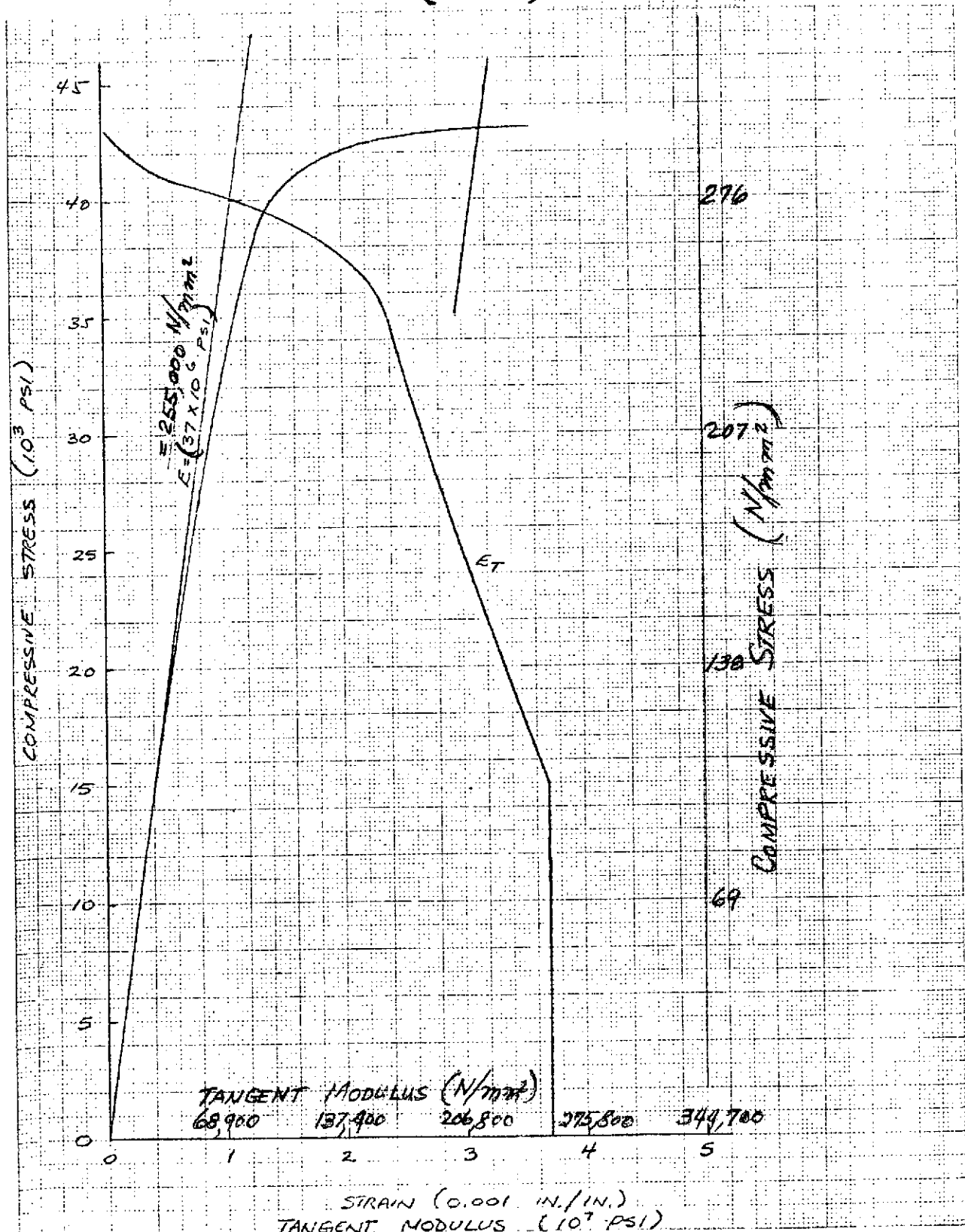
FIG. 12 : PLASTICITY REDUCTION FACTORS,
BERYLLIUM CROSS-ROLLED SHEET
ROOM TEMPERATURE

$\eta = \sqrt{E_T/E}$

$\eta = E_T/E$

F (10^3 psi)

F/η (10^3 psi)

F/η N/mm²

F N/mm²

FIG. 13.
PLASTICITY REDUCTION FACTORS
BERYLLIUM CROSS-ROLLED SHEET
315°C (600°F)
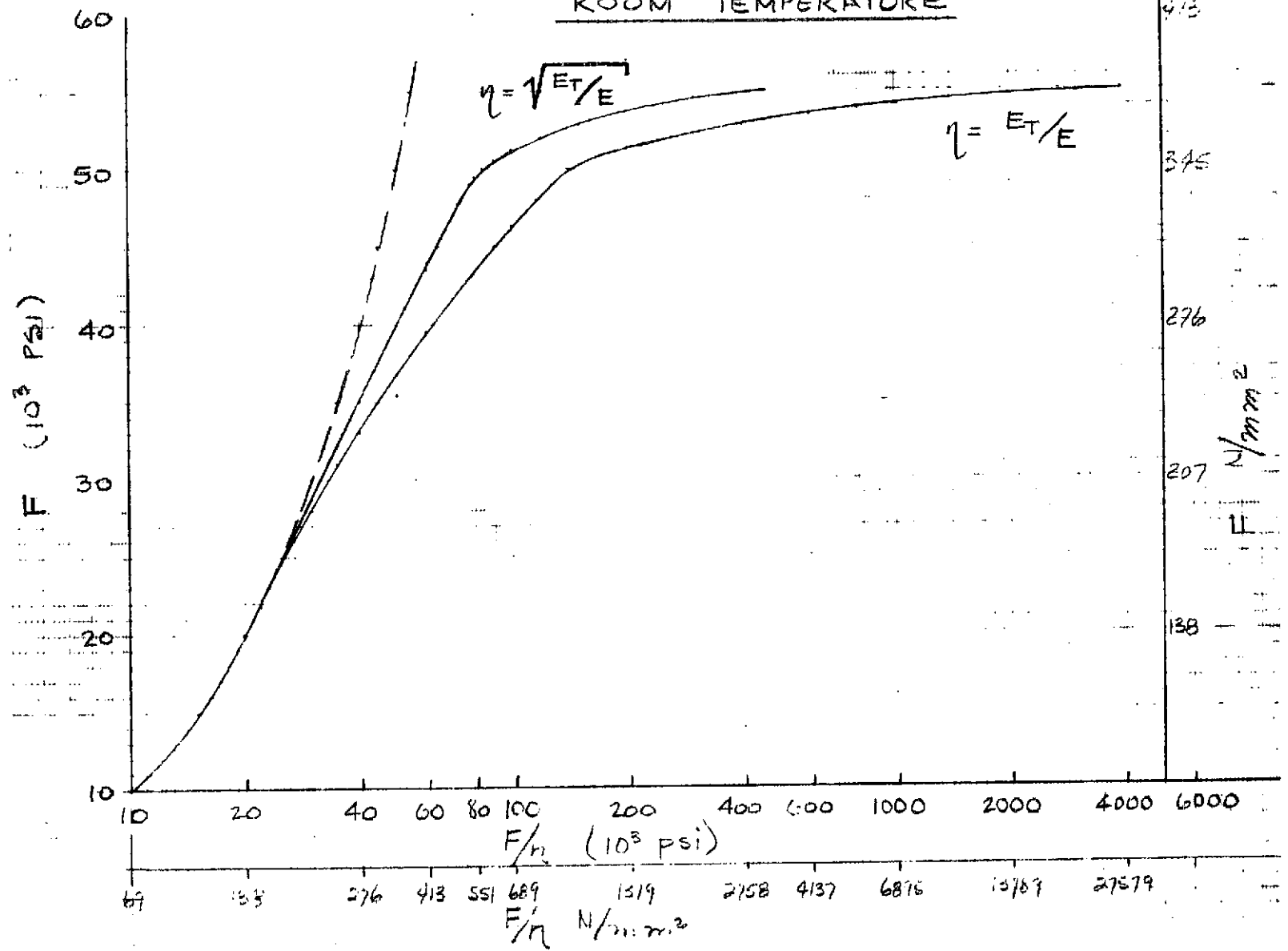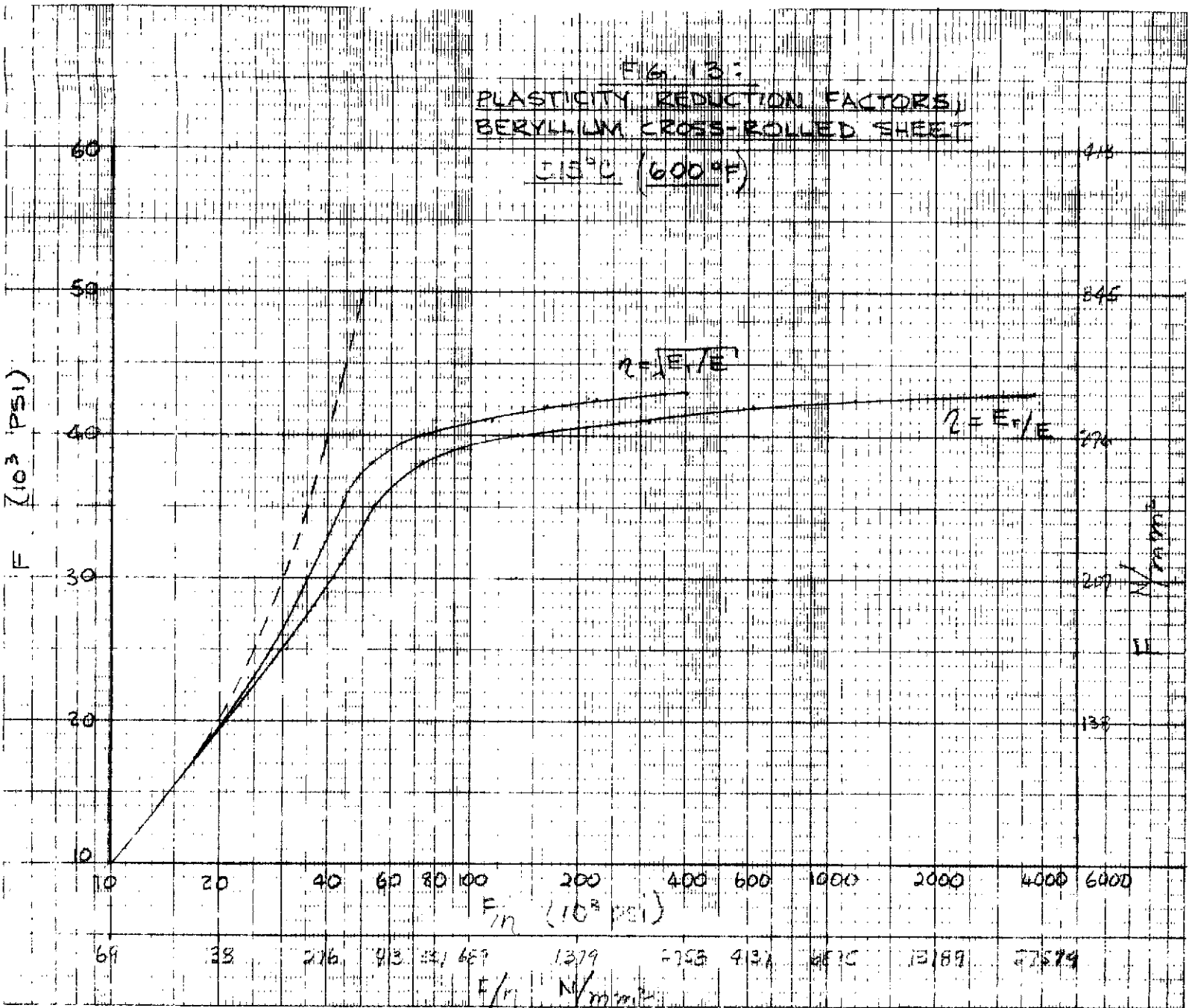
Appendix E

EM B1-M2-2.C

WEIGHT ANALYSIS OF
BERYLLIUM STRUCTURES

ENGINEERING MEMORANDUM

TITLE: WEIGHT ANALYSIS OF BERYLLIUM STRUCTURE PROTOTYPES FOR SPACE SHUTTLE - CONTRACT NAS 8-27739	EM NO: B1-M2-2C (Rev. C, 6-19-72) REF: DATE: 30 July 1971
AUTHORS: B. H. Chin	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT:

To document weight summaries of beryllium structures in layout design, design release and final assembly phases of development. Weight changes between succeeding phases will be recorded and explained.

RESULTS:

Page 3 tabulates the weight breakdown of each of the four beryllium structures. Beryllium and non-beryllium components are segregated.

This document presents the results of the analysis of the structural prototype weight trend.

DISCUSSION:

Component weight calculations were made from the following drawings with supplementary information as noted:

Drawing No.

   * SKS 100125 (5-27-71)   Compression Panel-Beryllium 29" x 80"

  ** SKS 100130 (6-22-71)   Compression Panel-Beryllium 48" x 72"

*** SKG 100127   Beryllium Thrust Structure-Truss 340" x 120"

     SKW 100128   Beryllium Shear Beam   360" x 100"

   * Beryllium gauge increased to .09" from .08" shown.

  ** Beryllium gauge increased to   .125" from .10" shown.

*** Components of individual truss members silver brazed together.

Material densities used were as follows:

Beryllium (Be) = .067 #/in^3

Titanium (Ti) = .160 #/in^3

Steel   (Fe) = .283 #/in^3

REVISION A   of 1-3-72

Revision A reflects the following changes:

a) EM number changed from B1-M3-2 to B1-M2-2A.

b) Kg wts corrected.

c) Design weights for the released uniform load panel (29 x 80) and the concentrated load panel (48 x 72) drawings are entered in Column 2 of Page 3.

REVISION B of 3-30-72

Revision B reflects the following changes:

a) Design weights for the released dwgs. of the shear beam (360 x 100) and the truss beam (340 x 120) are entered in Column 2 of page 3.

REVISION C of 6-19-72

Revision C reflects the following changes:

a) Actual weights of the uniform load panel and the concentrated load panel are entered in Column 3 of page 3.

b) Calculated weight of SKC-201001 Rev. A in Column 2 of page 3 corrected.

c) Added page 3A, discussion on potential weight savings.

d) Calculated weight of SKJ-201002 Rev. B in Column 2 of page 3 corrected.

WEIGHT HISTORY

ITEM	LAYOUT DESIGN		DESIGN RELEASE		ACTUAL WEIGHT	
Compression Panel (29 x 80)	SKS-100125		SKJ-201002 Rev. B		SKJ-201002 Rev. C	
(Uniform Load)	kg.	(lbs)	kg.	(lbs)	kg.	(lbs)
Be Panel	6.2	(13.7)	8.5	(18.8)	8.4	(18.5)
Be Stiffeners(Incl.Doublers)	11.3	(24.9)	15.2	(33.6)	14.7	(32.5)
Ti End Plates	1.6	(3.6)	8.9	(19.5)	10.4	(23.0)
Fasteners	3.6	(7.9)	5.5	(12.0)	4.2	(9.3)
Total	22.7	(50.1)	38.1	(83.9)	37.7	(83.3)
Compression Panel (48 x 72)	SKS-100130		SKC-201001 Rev. A		SKC-201001 Rev. B	
(Concentrated Load)	kg.	(lbs)	kg.	(lbs)	kg.	(lbs)
Be Panel	13.1	(28.8)	14.7	(32.4)	14.1	(31.1)
Be Stiffeners	10.2	(22.5)	12.0	(26.4)	12.2	(27.0)
Ti End Plate	1.3	(2.9)	13.7	(30.2)	13.7	(30.3)
Ti Column Assys	14.0	(30.9)	18.6	(41.1)	18.3	(40.3)
Fasteners	5.8	(12.7)	7.1	(15.6)	9.0	(19.9)
Doublers			6.8	(14.9)	6.6	(14.5)
Total	44.4	(97.8)	72.9	(160.6)	73.9	(163.1)
Be Shear Beam (360 x 100)	SKW-100128		SKR-201020			
	kg.	(lbs)	kg.	(lbs)		
Be Panels	147	(324)	151	(334)		
Be Stiffeners	146	(322)	168	(371)		
Be Cap. Top	70	(154)	111	(245)		
Be Cap. Bottom	108	(237)	199	(439)		
Stl. Thrust Posts	329	(725)	346	(762)		
Stl. End Posts	194	(427)	232	(511)		
Fasteners & Misc.	122	(270)	50	(111)		
Total	1116	(2459)	1257	(2773)		
Be Truss (340 x 120)	SKG-100127		SKR-201017			
	kg.	(lbs)	kg.	(lbs)		
Be Members	331	(729)	612	(1347)		
Ti Gussets/Lockalloy Gussets	103	(226)	227	(500)		
Fasteners	34	(75)	49	(107)		
Total	468	(1030)	888	(1954)		

POTENTIAL WEIGHT SAVINGS

The present designs of the uniform load panel, SKJ 201002, and the concentrated load panel, SKC 201001 Rev. A, utilize titanium for the end fittings and monel for the attachments due to cost factors and schedule requirements. However, investigation shows that a substantial weight savings can be accomplished by substituting Lockalloy (Be 38 Al) material for the end fittings (designed by stiffness compatability with the panel) and substituting titanium fasteners for the monel fasteners. Lockalloy vs titanium properties are as follows:

	Be 38 Al Lockalloy	6 Al 4V Titanium
At 600°F		
F_{tu} =	25 KSI	100 KSI
F_{ty} =	22 KSI	84 KSI
F_{cy} =	17 KSI	90 KSI
F_{bry} =	20 KSI (Estimated)	118 KSI
E =	27.5×10^6 psi	13.1×10^6 psi
	$= 0.076$ lbs/$_{in}3$	0.160 lbs/$_{in}3$

Maintaining strain compatibility with beryllium by the ratio of the moduli, $37.0/_{27.5}$, and staying within the constraints of the lower mechanical properties of the Lockalloy material, preliminary analyses show the savings as depicted in the following table. The fastener weights are reduced directly as the ratio of the densities of titanium and monel, $.160/_{.319}$.

POTENTIAL WEIGHT SAVINGS BY REPLACING TITANIUM

END FITTINGS WITH LOCKALLOY FITTINGS AND REPLACING

MONEL RIVETS WITH TITANIUM RIVETS

Uniform Load Compression Panel, SKJ 201002, Rev. C
(29" X 80")

	Actual Wt.		Improved Design			Wt. Savings	
	Kg	(lbs)	Kg	(lbs)		Kg	(lbs)
Be Panel	8.4	(18.5)	8.4	(18.5)		--	--
Be Stiffeners (incl. doublers)	14.7	(32.5)	14.7	(32.5)		--	--
End Plates	10.4	(23.0)	4.0	(8.8)	(Lockalloy t = .250)	6.4	14.2
Fasteners	4.2	(9.3)	2.1	(4.7)		2.1	(4.6)
Totals	37.7	(83.3)	29.2	(64.5)		8.5	(18.8)

Concentrated Load Compression Panel, SKC 201001, Rev. B
(48" X 72")

	Actual Wt.		Improved Design			Wt. Savings	
	Kg	(lbs)	Kg	(lbs)		Kg	(lbs)
Be Panel	14.1	(31.1)	14.1	(31.1)		--	--
Be Stiffeners	14.2	(27.0)	12.2	(27.0)		--	--
End Plate	13.7	(30.3)	4.9	(10.8)	(Lockalloy t = .280)	8.9	(19.5)
Column Assemblies	18.3	(40.3)	8.7	(19.2)	(same design)	9.6	(21.1)
Fasteners	9.0	(14.5)	6.6	(14.5)		4.5	(9.9)
Doublers	6.6	(14.5)	6.6	(14.5)		--	--
Totals	73.9	(163.1)	51.0	(112.6)		23.0	(50.5)

COMPRESSION PANEL - BERYLLIUM
SKS 100125

-1   Sheet   .09 .080 Be   x 1 ea.

     29 × 80
    (-) .0276 in² × 1507   }   .09 ×.067 = 13.7

-3   Channel   .09 .084 Be   x 9 ea

    (3.35 + 2.4 −.16) × 78.04   }   ×.09 ×.067   = 2.61
    (-) .0276 × 125   × 9 ea
                   —————
                    23.5

-5   Doubler   .09 .084 Be   x 2 ea

     4.14 × 29   }   ×.09 ×.067 × 2 ea   = 1.4
    (-) .0276 × 146

-7   End Plates   .125 Ti   x 2 ea

     2.13 × 29
     1.87 × 16.4   }   .125 ×.16 × 2 ea   = 3.6
    (-) .0276 × 122

Fasteners (est.) (steel)

Rivets (3/16ᴰ × 1/2)   .0055 × 90 ea = 0.5
       × 7/16   .005 × 1173 ea = 5.9   }   = 7.9
       × 9/16   <.006 × 244 ea   1.5

                ——————

         Total   50.1 LB

Top (Sect B-B)

$(2+2-.25).25 \times 2ea$ } $354 \times .067$ $= 85.5$

$5.4 \times .32$

Bottom (Sect G-G)

$(2+2-.25).25 \times 4ea$ } $123 \times .067$ $- 88.9$

$(5.4+5.6).32 \times 2ea$

Bottom (Sect C-C)

$(2+2-.25).25 \times 4ea$ } $123 \times .067$ $= 93.1$

$(5.4+6.4).32 \times 2ea$

Side (Sect H-H)

$(2+2-.25).25 \times 4ea$ } $130 \times .067$ $= 101.8$

$(5.4+7.0).32 \times 2ea$

Side (Sect A-A) = Side H-H + .64 × 130 × .067 $= 107.4$

Diagonal (Sect FF)

$(2+2-.25).25 \times 4ea$ } $170 \times .067$ $= 62.4$

$5.4 \times .32$

Diagonal (Sect C-C)

$(2+2-.25).25 \times 4ea$ } $170 \times .067$ $= 69.8$

$5.4 \times .44$

Vert (Sect E-E)

$(2+2-.25).25+(1.7 \times .25)$ } 4ea }

$(5.4 \times .32) + (10 \times .32)$ } 2ea } $117 \times .067 = 120.0$

GUSSETS

R2 $29 \times 7 + (6.5 \times 4) - (1\frac{1}{2} \times .7) - (\frac{14}{2} \times 6.5)$

R3 $27 \times 34) - (1.5 \times 1) - (13 \times 8.5)$

R1 $(\frac{14+11}{2} \times 4) - (1\frac{1}{2} \times 4) - (\frac{24}{2} \times 4) + (\frac{1}{2} \times 9)$ } $.25 \times .16 \times 2ea = 226.0$

PV2-L $(22 \times 8) - (\frac{25}{2} \times 7) - (\frac{6}{2} \times 12.6)$

PV1 $(37.5 \times 24) - (12 \times 7) - (6 \times 9)$

PV2-R $(\frac{12+24.5}{2} \times 32) - (7\frac{1}{2} \times 10)$

FASTENERS Ti Esth $5_x^{\#}$ A; BRAZE $23^{\pm}$ $= 75^{\pm}$ TOTAL = 1030 ℓB

Beryllium Shear Beam, SKW 100128

Be Panel Center

$$240 \times 96 \times .10$$
$$(2 \times 5 + 24) \, .0875 \times 96 \quad \Big\} \; .067 \qquad = 173.5$$

Be Panel End   × 2 ea.

$$62.5 \times 96 \times .1875 \times .067 \times 2 \, ea \qquad = 150.8$$

Stiffeners   Be   × 28 ea

$$(5 + 3 - .25) \, .25 \times 96 \quad \Big\}$$
$$(-) \quad 3 \times 19 \times .25 \qquad \Big\} \; .067 = 11.5 \times 28 \, ea = 322.2$$

Cap Top   Be

$$\left(\frac{1.15 + .65}{2} + \frac{1.15 + .57}{2} \right) \times 6 \times 125$$
$$\left(\frac{.64 + .4}{2} + \frac{.57 + .28}{2} \right) \times \frac{6 + 3}{2} \times 55 \quad \Big\} \; .067 \qquad = 154.1$$
$$(5 - .86) \, .5 \quad \times 360$$

Cap Bottom   Be

$$\left(\frac{1.92 + 1.33}{2} + \frac{1.92 + .86}{2} \right) \times 6 \times 125$$
$$\left(\frac{1.33 + 1.03}{2} + \frac{.86 + .33}{2} \right) \times 4.5 \times 55 \quad \Big\} \; .067 \qquad = 336.5$$
$$(6 - 1.39) \, .5 \times 360$$

Thrust Post Stl.

$$(5 \times .3) + (5.36 \times .18)$$
$$(3 + 3) \, .18 \qquad \Big\} \, 95 \quad \Big\} \; .283 \times 2 \, pichs \times 3 \, ea \qquad = 724.6$$
$$12 \times 3 \times 2.5$$

End Posts Stl.

$$(5 \times .2) + (2.5 \times .5 \times 2) \quad \Big\} \, 97 \quad \Big\}$$
$$5 \times 5 \times 1.5 \qquad \Big\} \; .283 \times 2 \, sches \times 2 \, ea \qquad = 426.8$$

Fasteners: (Est) (steel)

Bolts   5 $\Big\}$
Tivels   265 $\Big\}$ = 270

Total   2459. ct

-1 Sheet $\frac{.125}{.10}$ Be

$\quad$ 24×72 $\qquad$ .125 ×.067 × 2ea $\qquad$ = 28.8

$\quad$ (-) .0276 × 240

-3 Channel $\frac{.125}{.10}$ Be

$\quad$ (3+2.5-.2) 70.85 $\qquad$ .125 ×.067 × 6ea $\quad$ = 18.7

$\quad$ (-) .0276 ×120

-5 Doubler $\frac{.125}{.10}$ Be

$\quad$ 3.5×24 $\qquad$ .125 ×.067 ×2 ea $\qquad$ = 1.4

$\quad$ (-) .0276 × 200

-7 Doubler $\frac{.125}{.10}$ Be

$\quad$ 3 × 31.8 × .125 × .067 $\qquad$ = 0.8

-9 Angle $\frac{.125}{.10}$ Be

$\quad$ (1.5+1.5-.1)×19 $\qquad$ .125 ×.067 × 2ea $\quad$ = 0.9

$\quad$ (-) .0276 × 40

-11 Angle $\frac{.125}{.10}$ Be

$\quad$ (1.75+1.75-.1) × 2.8 × .125 ×.067 ×2 ea $\quad$ = 0.2

-13 Channel $\frac{.125}{.10}$ Be

$\quad$ (2.83+2.5-.2) ×11.8 × .125 ×.067 $\qquad$ = 0.5

-15 End Plate .125 Ti

$\quad$ 3.5×48

$\quad$ (-) 1.35×1.65×2   (-) 1.5 ×1.65 ×4 $\quad$ .125 × .16 = 2.9

$\quad$ (-) .0276 ×320

-301 Column Ti

$\quad$ (14×3 ×.1) + ($\frac{3+5.4}{2}$ ×15 ×.17) -

$\quad$ ($\frac{5.4+9.4}{2}$ × 24.8 ×.25) + (3.4×48)×24.6 ×.17 ×2ea)

$\quad$ [(2.15×.4) +(2.55×.2)+(1.2 ×.1)] ×3 ×2 ea $\qquad$ ×.16 = 15.8

-303 Column —same as -301 Column —4.2 in³ $\qquad$ = 15.1

Fasteners (est.) (steel) $\qquad$ = 12.7

$\qquad\qquad\qquad\qquad\qquad\qquad$ TOTAL $\quad$ 97.8 LB

Appendix F

EM B1-M2-3

STRUCTURES CRITERIA AND

PANEL SKC 201001 ANALYSIS

ENGINEERING MEMORANDUM

TITLE: 3.3STRUCTURAL CRITERIA AND ANALYSES OF BERYLLIUM PANEL SKC 201001	EM NO: B1-M2-3 REF: DATE: 10-4-71
AUTHORS: G. S. Fuchigami *SF* P. Stern	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

To document structural analyses summaries in layout design, design release, and final assembly phases of development.

RESULTS

The design details of the concentrated load panel are shown on SKC 201001. The preliminary analyses of this panel are presented in pages 2 through 12 and current results of the STAGS computer analysis are discussed.

DISCUSSION

The initial design as proposed on Dwg. SKS 100130 showed a 24 in. long titanium fitting to distribute the concentrated load into the panel. Titanium was adopted for this fitting because of the extremely thick sections, required by the stress levels in a beryllium fitting. In order to decrease the excessively high stresses in the area at the end of this fitting, its length has been increased to 36 in. In addition, its thickness has been increased to provide for compatible strain with the beryllium panel.

The present design of the joints is based on the usage of squeezed monel rivets. Preliminary tests show that these rivets fill the hole upon installation, thus providing for uniform load distribution. Attachments which do not fill the hole such as Hi-Loks will require very close tolerance fits in a multi-rivet configuration in beryllium structures. However, because monel rivets are heavy, tests are underway to evaluate squeezed titanium rivets or blind Huck-type titanium bolts as candidate fasteners.

The most recent STAGS analyses of this panel show that the load distribution at the distributed load end does not meet the peaking criteria of 130 percent (see pages 13 to 19). The model is being altered to more accurately simulate the load application and edge restraints, both of which would influence the areas of high peaking at the center and edges. Modifications to the structure may be necessary if refinements of the analyses verify this condition. Meanwhile, a (REXPAT) computer analyses has been initiated to determine the stress distribution in the area adjacent to the distributed load take-out fitting.

Subjects as presented are: design criteria, trade considerations for panel concepts, material data for structural components and panel analysis.

I DESIGN CRITERIA

Compression Panel With Concentrated Load

Des. Temp = 600°F

Safety Factors: 1.1 on yield
1.4 " ultimate

Design loads:
Concentrated load = 350,000 lb ultimate

$$= \frac{350,000}{1.4} = 250,000 \text{ lbs limit}$$

Peaking allowable at closeout = 130

Panel edges to be simply supported by test fixture.

Panel Closeout members to be representative of a production splice and provide reasonable shear and tension capability.

Basic panel size = 48" x 72", panel loaded in the long direction

Material: Panel = beryllium

Load introduction = optional

TABLE 1

TRADE CONSIDERATIONS FOR PANEL CONCEPTS

	ADVANTAGES	DISADVANTAGES
Panel Construction		
1. Material Distribution		
Monocoque Design (Transversely stiffened panels)	Mfg simplicity. Min. design costs.	Structurally inefficient for uniaxial loading. Low strength to weight.
Longitudinally Stiffened Panels	Structurally efficient. Stringer spacing, stringer cross-sections gages can be optimized. High strength to weight. Geometry is amenable to concentrated load fittings.	Increased design complexity. Increased mfg. complexity.
Z Stiffeners	Stable under bending loads.	Higher mfg. costs then [s.
[Stiffeners	Can be made with hot dies with single pass forming.	Shear center outside of web; ∴ member tends to twist in bending.
⊓ Stiffener	Stable under bending loads.	High mfg. costs; heavy.
2. Fastening		
Bonding (Bloomingdale HT242 epoxy-phenolic adhesive)	Uniform load distribution. Eliminates stress concentration effects of attachment holes.	High temperature structural data not available. Joint preparation is very critical for reliability - cleanliness, smoothness, clamping forces, etc. Difficult to disassemble for inspection and repair.
Brazing (Al - 12% Si Alloy EZ-Flo #3 Incusil #10)	Uniform load distribu- Eliminates stress con- centration effects of attachment holes.	High temperature structural data not available. Method not readily adaptable to large components -- clamped up assemblies have to be cured in an oven

TABLE 1 (Cont'd)

	ADVANTAGES	DISADVANTAGES
Close-Out Construction 1. **Materials** Aluminum (2024-T4 6061-T4 7075-T6)		Structurally inadequate at 600° F. $F_{t_{y600°}} = 7\text{-}11\% \; F_{t_{y R.T.}}$ $E_{600°} = 70\% \; E_{R.T.}$ $e_{600°} = 70\text{-}100\%$ $Creep_{600°} = $ Large $\alpha = 14\text{-}15 \; in/in/°F \times 10^{-6}$
Magnesium (HM21A-T8)	Relatively high modulus at 600° F $(E_{600°} = .8E_{R.T.})$	Structurally inadequate at 600° F. $F_{t_{y600°}} = 50\% \; F_{t_{y R.T.}}$ $F_{bry\,600°} = $ Low (11.5 ksi) $e_{600°} = 15\text{-}40\%$ Creep = Large $\alpha_{600°} = 15.6 \; in/in/°F \times 10^{-6}$
Titanium (6AL-4V)	Excellent mech. properties @ 600° F. Lighter weight than steel $\alpha = 5.8 \; in/in/°F \times 10^{-6}$	Machineability - fair Weldability - fair Formability - fair
Austenitic Steel (18-8, 301, 321, 347)	$E_{600} = 88\% \; E_{R.T.}$ $\alpha = 10.2 \; in/in/°F \times 10^{-6}$	Lower strength to wt. ratio than titanium $e_{600} = $ Large $Creep_{600} = $ Large
Lockalloy (Be-38A1)	$E_{600} = 95\% \; E_{RT}$ $\alpha = 9.8 \; in/in/°F \times 10^{-6}$ Light weight.	Cost is high. Thick sheets & plates will require mfg. tool development. Procurement lead time.

TABLE 1   (Cont'd)

	ADVANTAGES	DISADVANTAGES
2. Fastening (Cont'd)		
Bond + Rivets (Epoxy resin adh. 123 cement with 9615-10 hardner.)	Uniform load distribution	High temperature structural data not available. Room temp. tests show some specimens developed full adhesive shear & some sheared rivets.
Monel Rivets	Good shear capabilities at 600° F. Can be squeezed easily. Coeff. therm. exp. is compatible with beryllium.	Heavy; density = .319 lbs/in^3
Titanium Rivets (Annealed)	Good shear properties at 600° F. Light; density = .163 lbs/in^3. Process tests show squeezing feasible with filled holes.	More difficult to squeeze than monel rivets.
Titanium Beta III Rivets	Excellent shear properties at 600° F. Light; density = .163 lbs/in^3 Process tests show squeezing feasible with filled holes.	More difficult to squeeze than monel rivets.
Titanium Blind Bolt (Huck Type)	Good shear properties at 600° F. Can be installed from one side. Light weight.	More expensive than rivets. Possible installation damage when spindle is detached.
Titanium Hi-Loks & Screws	Good shear properties at 600° F. Light weight.	These fasteners do not fill the holes at installation (the shank does not swell), and may lead to uneven load distribution and subsequent cracking between adjacent holes.

II MATERIAL DATA
Compatibility of Materials Used

	BERYLLIUM Cross Rolled Sheet		AUSTENITIC STEELS (18-8) 301,302,321,347 (ANNEALED)		[1][2] TITANIUM 6AL-4V SHEET (ANNEALED)		[3] LOCKALLOY Be-38Al SHEET		MAGNESIUM HM21A-T8 SHEET	
	R.T.	600°F	R.T.	600°F	R.T.	600°F	R.T.	600°F	R.T.	600°F
DENSITY - lbs/in³	0.066		0.29		0.160		0.076		0.064	
MELTING POINT - °F	2345								1100	
COEFF. THER. EXP. 10⁻⁶ in/in/°F	6.0	7.7	9.2	10.2	~5.0	5.8		9.8	14.0	15.6
POISSONS RATIO	.020-.10		.29				.14			
CORROSION RESISTANCE									FAIR - POOR	
FORMABILITY					3-5 t				6 t	
WELDABILITY					FAIR TO GOOD				GOOD	
CREEP					EXHIBITS EXAGGERATED BAUSHINGER EFFECT IN PLASTIC RANGE				@ 600°F, 0.2% CREEP @ 70 KSI IN 5 HRS.	
MECHANICAL PROPERTIES (KSI)										
F_{tu} L	69.0	50.5	75	56	134	100	44	25	33	11
F_{tu} T	68.0	48.0								
F_{ty} L	45.0	25.0	30	20	126	84.5	31	22	18	9
F_{ty} T	45.0	34.5								
F_{cy} L	46.0		35	26	132	90	28	17	15	10
F_{cy} T	46.0				132					
F_{su}	57.0	33.5	40		79	59	23		21	10
F_{bru} e/D = 1.5	100				197	147			47	12
F_{bru} e/D = 2.0	125	136	150	92	252	189	81		56	14.5
F_{bry} e/D = 1.5					171	118			29	11.5
F_{bry} e/D = 2.0			50	39	208	143	55		29	11.5
e	5 %	31 %	50 %		8 %	12 %	5 %		6 %	15-40 %
E, E_c, psi	42×10⁶	E=37×10⁶ Ec=41×10⁶	29×10⁶	25.9×10⁶	E=16.0×10⁶ Ec=16.4×10⁶	13.1×10⁶ 13.4×10⁶	28×10⁶	27.5×10⁶	6.5×10⁶	5.2×10⁶
G psi	20×10⁶		12.5×10⁶	9.5×10⁶	6.2×10⁶		12.5×10⁶		2.4×10⁶	

Ref. Structural Materials Handbook (LMSC) unless otherwise noted.

[1] Ref. MIL-HDBK-5
[2] Ref. AD 463625 L, Ti Design Hdbk 1965
[3] LMSC 679606, "STR. EFF. & DES. DATA FOR Be-ALLOY STRUCT." C.F. MacLEAN, et al, 1967

III RIVET DATA

Monel

(Nickel - Copper alloy)

Ref Huntington Alloy Products Div,
The International Nickel Company, INC,

Alloy 400

Nickel	63.00 - 70.00
Carbon	0.30 max.
Manganese	2.00 "
Iron	2.50 "
Sulfur	0.024 "
Silicon	0.50 " "
Copper	Balance

Density = 0.319 lb/in^3
Melting range = 2370 - 2460 °F
$E = 26.0 \times 10^6$
$\mu = 0.32$

Shear Strengths: Rivet wire : (Annealed)

R.T. = 48,500 psi
600°F = 45,000 "   (30 minutes @ Temp)
800°F = 37,000 "   "   "
1000°F = 29,000 "   "   "

Mean linear expansion, $in/in/°F \times 10^{-6}$

70	=	—
200	=	7.7
400	=	8.6
600	=	8.8
800	=	8.9
1000	=	9.1

Monel (Cont.)

Rivet Strength (Solid Protruding Head)
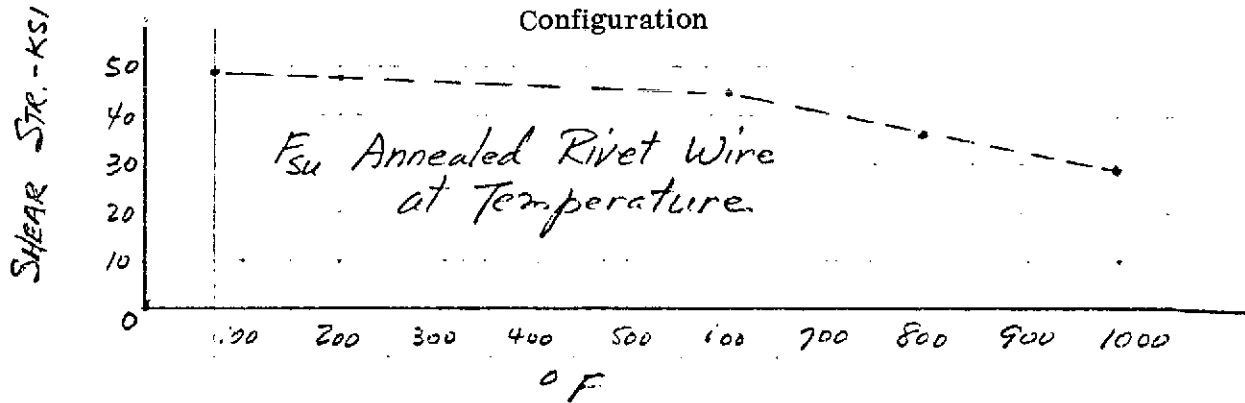
$$@ \ 200°F, \quad use \ \frac{47}{49} = .96 \ R.T. \ values \ of \ MIL-HDBK-5$$

$$@ \ 600°F, \quad use \ \frac{41}{49} = .84 \ R.T. \quad '' \qquad '' \qquad ''$$

SHEAR STRENGTHS OF MONEL RIVETS *

	Sheet t = .090		Sheet t = .125	
	Rivet Size		Rivet Size	
	5/32	3/16	5/32	3/16
	(lbs)	(lbs)	(lbs)	(lbs)
R.T.				
Single Shear	973	1400	973	1400
Double ''	1880	2580	1940	2800
200°F				
Single Shear	933	1325	933	1325
Double ''	1800	2480	1860	2690
600°F				
Single Shear	817	1175	817	1175
Double ''	1580	2250	1630	2350

* Ref. Tables 8.1.1(b) & 8.1.1.1(b) MIL-HDBK-5

Titanium Rivets

Common titanium rivet materials are as follows:

Unalloyed titanium,

$Ti - 13V - 11 Cr - 3Al$

$Ti - 4Al - 4Mo - 4V$

Ref: Aircraft Des. Hdbk on Titanium, Aug. 1965, Battele Mem. Institute

Made from wire and rod.

Mechanical Properties:

Ref MIL-HDS-5

Unalloyed titanium: $F_{su} = 40$ KSI @ R.T

$= 20$ " " $600°F$

$Ti - 13V - 11Cr - 3Al$: $F_{su} \cong 92$ KSI @ R.T.

$\cong 79$ " " $600°F$

$Ti - 4Al - 4Mo - 4V$: $F_{su} \cong 80$ KSI @ R.T.
(Estimated Shear Values) $\cong 60$ " " $600°F$

IV CONCENTRATED LOAD PANEL (SKC-201001)

Configuration
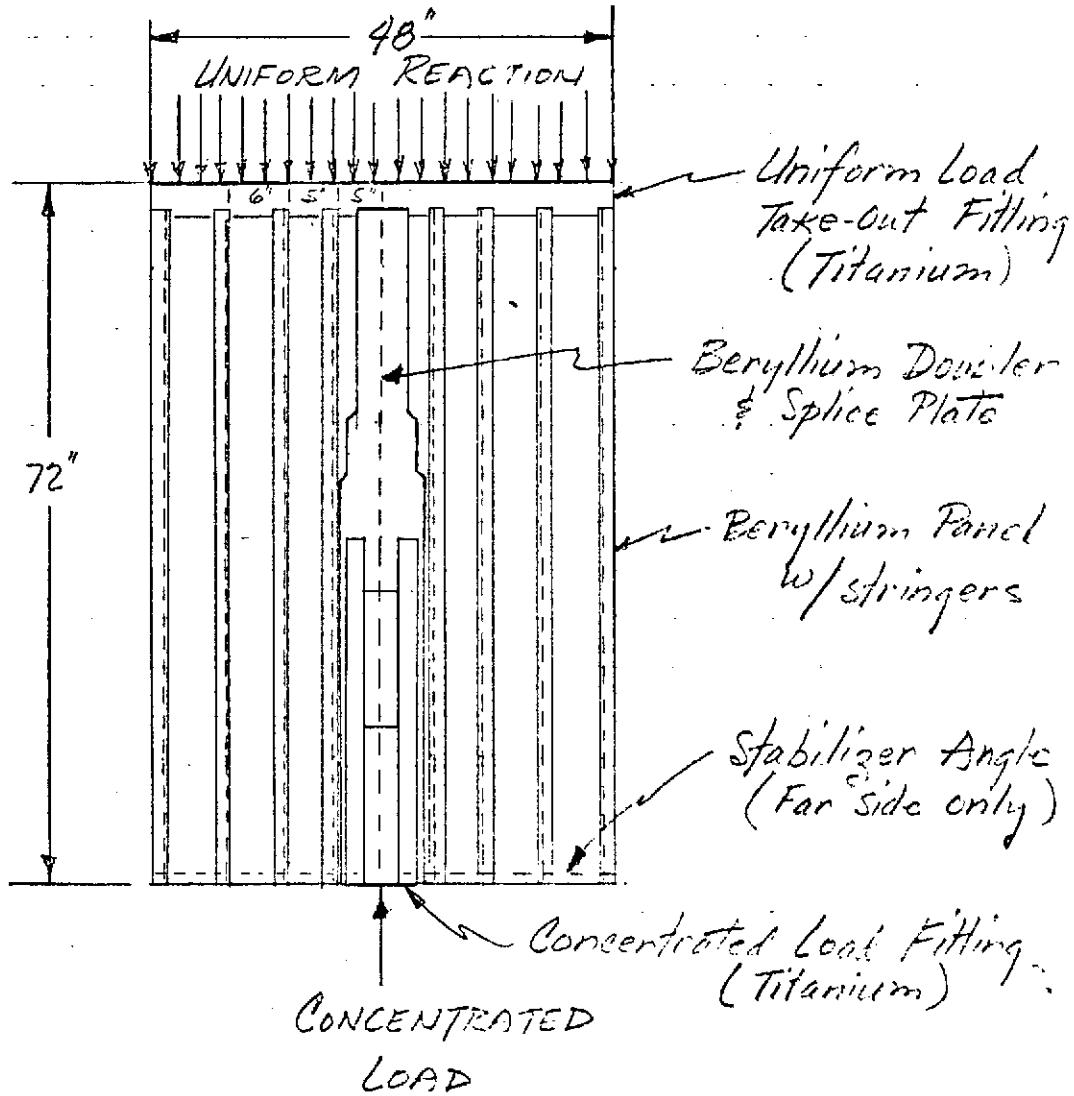
Concentrated Load Fitting

Configuration

6AL-4V TITANIUM — MAT'L PROP:

WELDED ASS'Y

@ 600°F, $F_{tu} = 96$ KSI

$F_{ty} = 80$ "

$F_{cy} = 85$ "

$E = 13.1 \times 10^6$ psi

$\leftarrow 5" \rightarrow \leftarrow 5" \rightarrow \leftarrow 5" \rightarrow$

3" Be [

3.50"

3.50"

.25

.125 Be Sheet

$\frac{3}{16}$ Rivets

Titanium Stabilizer Angle

$\frac{1}{4}"$ Monel Rivets For Fitting Only

CONCENTRATED LOAD FITTING 6AL-4V Titanium

$\frac{3}{4}"$ For 16"

$\frac{3}{8}"$ For next 14"
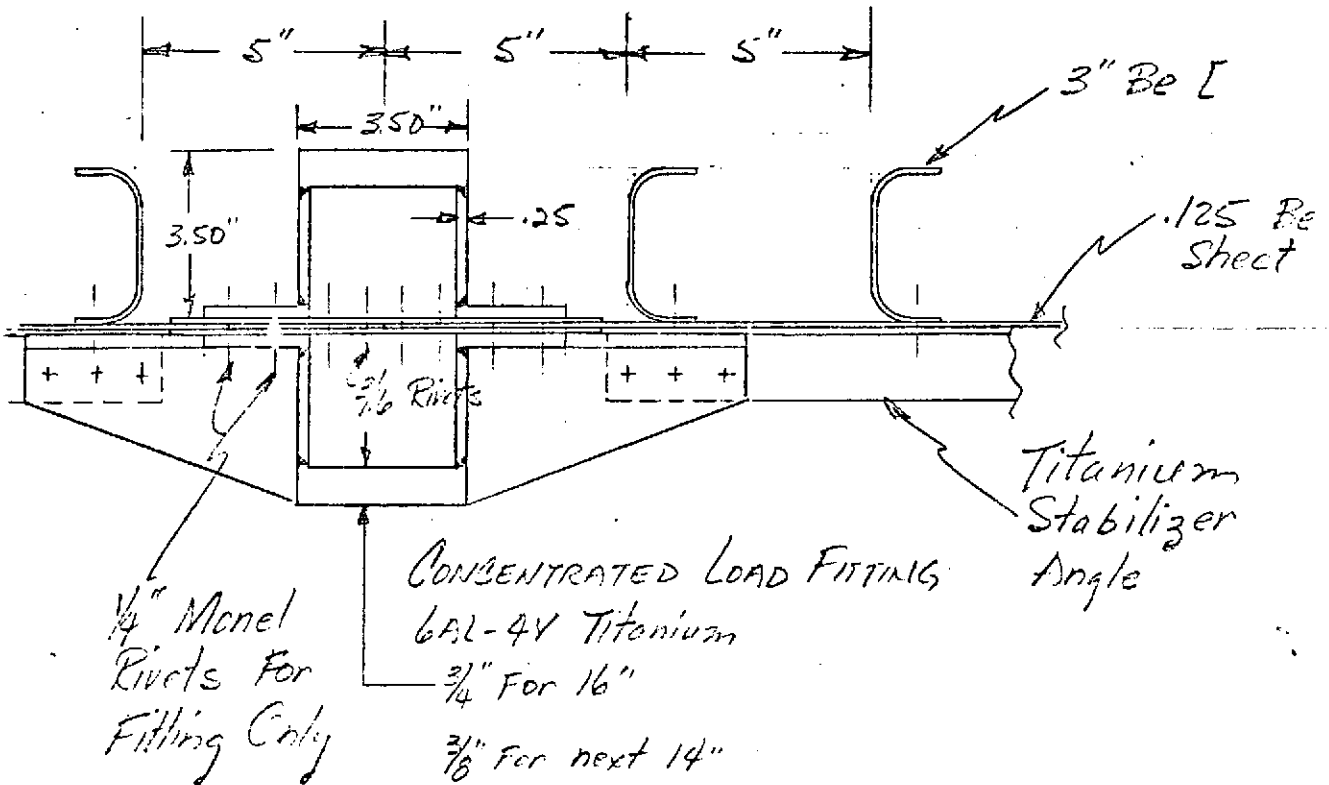
Concentrated Load Fitting (Cont.)

<u>Rivet Reqments</u> ($3/16$" Monel)

Number of rivets req'd in double shear:

$$N = \frac{350,000}{2350} = 149 \qquad \underline{Too \ many}$$

Try $1/4$" Monel Rivets.

Single Shear = $.84(2540) = 2130$ lbs

$$N_{req'd} = \frac{350,000}{2(2130)} = 82.2$$

<u>Use</u>

Uniform Load Take-Out Fitting

Configuration

.125 Be Sheet

3" Be. [

#6 Rivets

6AL-4V Ti
Fitting

Machined Surface

$P_{ult} = 7300$ lbs/in
+ 30% Peaking

Test
Fixture

1 3/4" 1 3/4"

3/4"

3/4"

3/4"

72"

P
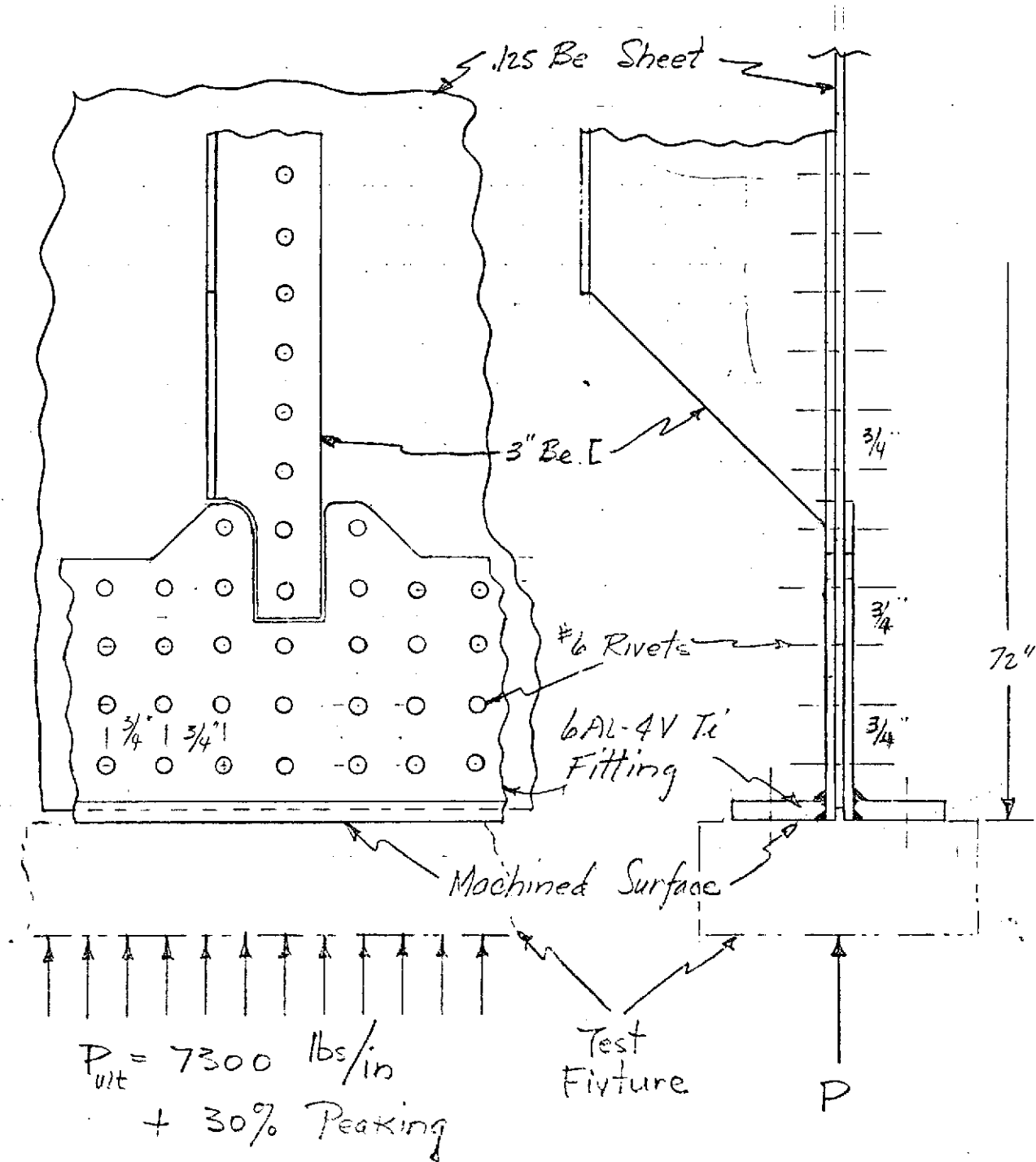
Uniform Load Take-Out Fitting (Cont.)

RIVETS

Bearing on the .125 sheet is critical.

Using same ratio as Titanium allowables:

$$(R.T.) \quad F_{bry (Be)} = \frac{F_{bry(Ti)}}{F_{bru(Ti)}} \times F_{bru (Be)} =$$

$$= \frac{163}{191} \times 100,000 = 85,000 \; psi$$

$$(600°F) \quad = \frac{112}{163} \times 85,000 = 55,000 \; psi$$

$$load \; per \; rivet = \frac{7300(.75)}{4} = 1370 \; lbs$$

$$A_{br} = .188 (.125) = .0235 \; in^2$$

$$f_{br} = \frac{1370}{.0235} = 58,300 \; psi$$

$$M.S._{bry} = \frac{55,000}{58,300} - 1 = -.06$$

O.K. because the estimated bearing allowable is conservative

ITEM	COLUMN NO.	1	2	3	4	5	6	7	8	9	10	11
	DESCRIPTION	a	y	ay	ay^2	I_{ox}	x	ax	ax^2	I_{oy}	axy	I_{oxy}
	OPERATION			①②	②③			④⑤	⑥⑦		⑧⑨	
1	.70 × .125	.087	1.562	.1370	.214	—						
2	90° Bend × .125	.135	1.314	.1775	.233	.00617						
3	1.75 × .125	.219	0	—	—	.05570						
4	90° Bend × .125	.135	-1.314	-.1775	.233	.00617						
5	.700 × .125	.087	-1.562	-.1370	.214	—						
6												
7												
8												
9												
10												
11												
12												
13												
Σ		.663		—	.894	.06804						

I_x

$$\bar{y} = ⑫ = \frac{\Sigma ay}{\Sigma a} = \frac{②}{①} = \underline{0.0} \text{ in.}$$

$$I_x = ⑬ = -\bar{y}\Sigma ay + \Sigma ay^2 + \Sigma I_{ox}$$

$$= -⑫③ + ④ + ⑤$$

$$= \underline{.962} \text{ in.}^4$$

$$P_x = \sqrt{\frac{I_x}{\Sigma a}} = \sqrt{\frac{⑬}{①}} = \underline{1.20} \text{ in.}$$

I_y

$$\bar{x} = ⑭ = \frac{\Sigma ax}{\Sigma a} = \frac{⑦}{①} = \underline{\hspace{1cm}} \text{ in.}$$

$$I_y = ⑮ = -\bar{x}\Sigma ax + \Sigma ax^2 + \Sigma I_{oy}$$

$$= -⑭⑦ + ⑧ + ⑨$$

$$= \underline{\hspace{1cm}} \text{ in.}^4$$

$$P_y = \sqrt{\frac{I_y}{\Sigma a}} = \sqrt{\frac{⑮}{①}} = \underline{\hspace{1cm}} \text{ in.}$$

$$I_{xy} = -\bar{y}\bar{x}\Sigma a + \Sigma axy + \Sigma I_{oxy} = -⑭③ + ⑩ + ⑪ = \underline{\hspace{1cm}} \text{ in.}^4$$

1. NOTE SIGN OF I_{xy} MAY BE POSITIVE OR NEGATIVE.

2. I_{oxy} IS PRODUCT OF INERTIA OF ITEM ABOUT CENTROIDAL AXES PARALLEL TO ARBITRARY AXES.
   I_{oxy} = 0 IF ITEM IS SYMMETRICAL ABOUT EITHER AXIS.

3. x HORIZONTAL (+) TO RIGHT, FROM ARBITRARY y AXIS.
   y VERTICAL (+) UP, FROM ARBITRARY x AXIS.

STAGS ANALYSES - Concentrated Load Panel

As requested in the second monthly progress report (LMSC A993378) the skin gage of the concentrated load panel has been increased from 0.100 in. to 0.125 in. Along with this change the concentrated load fitting has been redesigned and is made of titanium instead of beryllium. Figure 1 shows a schematic of the panel under investigation at the present time.

Because of symmetry only one-half of the panel was analyzed. The x coordinate has its origin on the edge where the concentrated load is applied and the y coordinate has its origin along the panel symmetry line as shown in Fig. 1. Also presented in this figure are the boundry conditions imposed.

A number of STAGS runs have been made in order to size the load fitting. This was necessary since the titanium has an elastic modulus which is about 0.35 times that of beryllium. Thus for strain compatibility it was necessary to increase the area of the titanium member. The latest computer runs include a uniform load take-out fitting.

Axial stress resultants (N_x - #/in) due to a one pound load on the concentrated load fitting are shown in Figs. 2 and 3. In Fig. 2, N_x is plotted against x along the symmetry line (y = 0), while N_x is plotted against y along x = 62.0 in. and x = 72 in. in Fig. 3. Note that these are stress resultants of the skin only. In order to compute stress N_x must be divided by the thickness. Then in order to obtain the stress for 350,000# these values must be multiplied by 1.75×10^5. For these computations the skin thickness is 0.125 in. and the thickness of the doubler at x = 72 in. is 0.25 in.

In Fig. 2 the load variation between x = 0 and 36 in. peaks in two locations due to the manner in which the stiffener was tapered in STAGS. (It was modeled as three different uniform stiffeners.) The peak between x 69.5 in. and 72 in. is due to the load carried by the doubler. It is assumed in the STAGS program that the stiffeners are compact beams and are strained the same amount at the skin joint. The actual load introduction on the physical model is through rivets between the fitting and skin. This should alter the stress distribution shown in Fig. 2. At present it is not known how much a variation this will make.

It is seen in Fig. 3a for x = 62.0 in. that N_x is fairly uniform in the y direction. At the uniform load take-out fitting (x = 72.0 in.) it was anticipated that there would be no more than a 30 percent variation of the average stress. However, as seen in Fig. 3b there is a load peak at the symmetry line as well as along the boundary (y = 23.65 in.). As noted previously, the peak at y = 0 is due to the doubler whereas the peak at the edge is probably due to the constraint placed on the deformation in the y direction. The peak at y = 23.65 in. is almost within the 30 percent range; however, further study is required for the peak at y = 0. Two possible modifications are planned in order to bring the panel within design limitations. The first is to introduce the load at the rivet attachments. This is an artificial method of distributing the load into the skin. The other modification would be a redesign of the uniform load take-out fitting so that it extends further into the panel.

Figures 4 and 5 show the bifurcation buckle mode (w is the normal displacement of the panel) along various lines of constant x (Fig. 4) and along various lines of constant y (Fig. 5). The buckle load for this model is 374,000#. From the standpoint of buckling the panel is well designed. The major problems involve the prebuckling stress distribution. Future models will investigate different load introductions and uniform load take-out fittings.
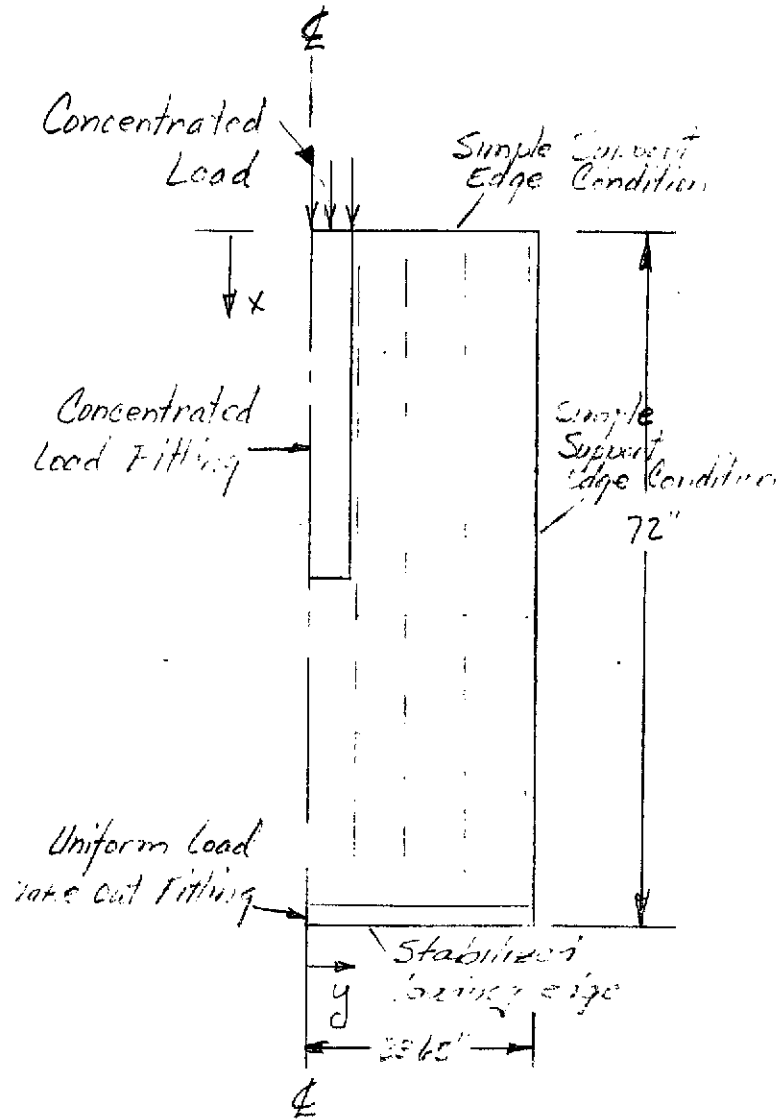
Figure 1   Concentrated Load Panel
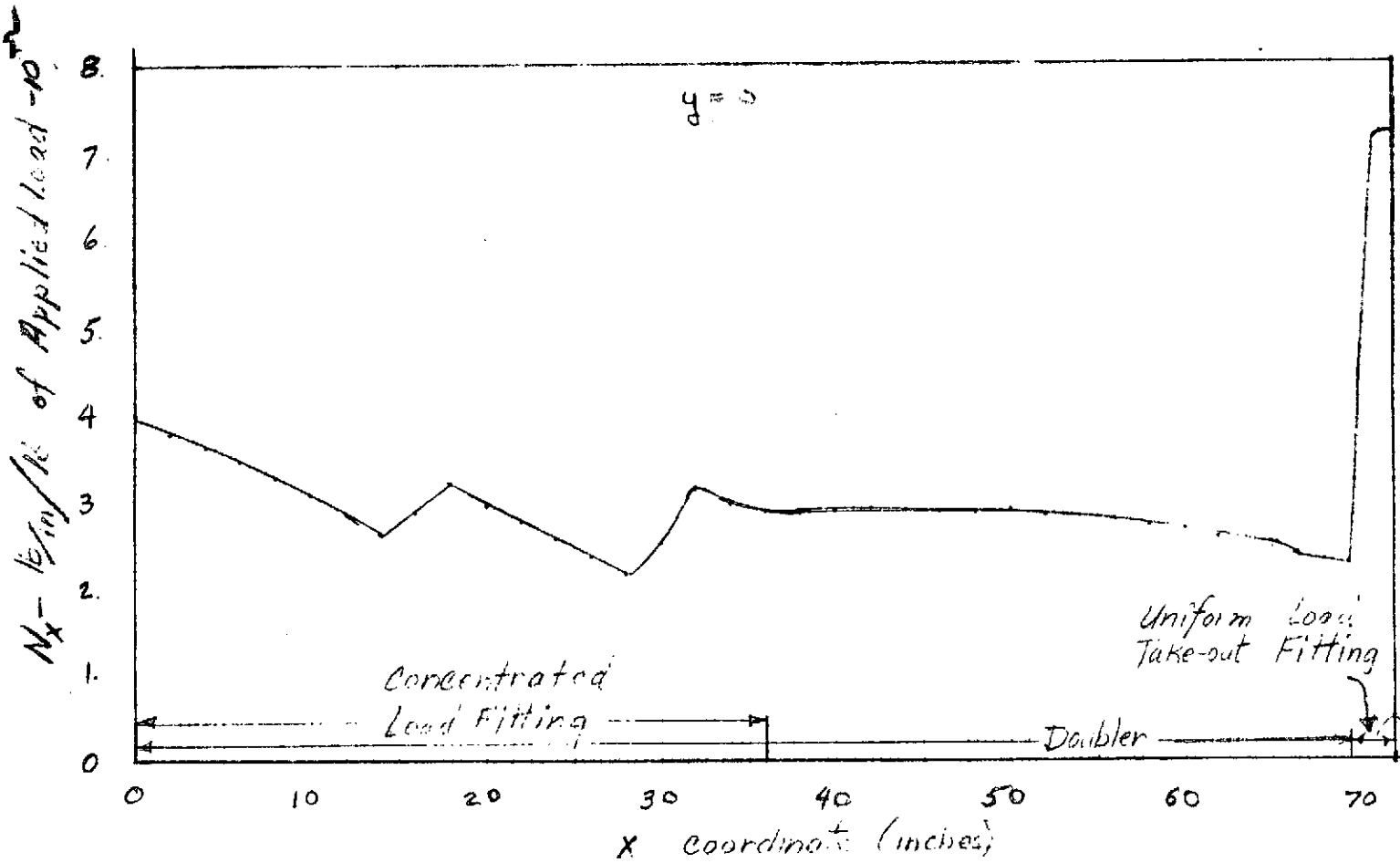
Figure 2   Stress Resultant N_x along y = 0

x = 62.0 in.

(3a)

(3b)
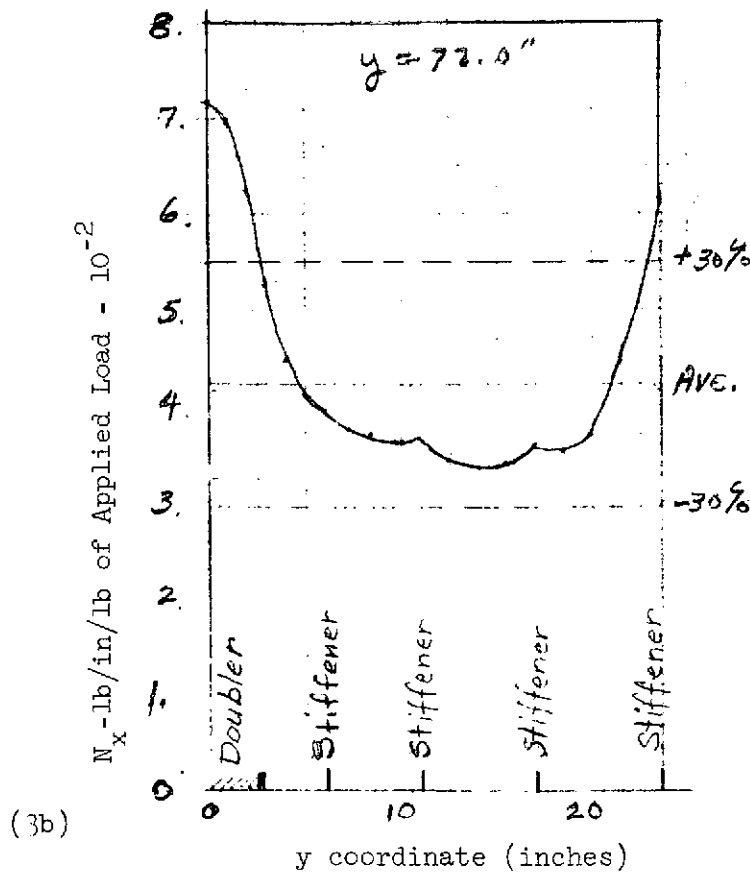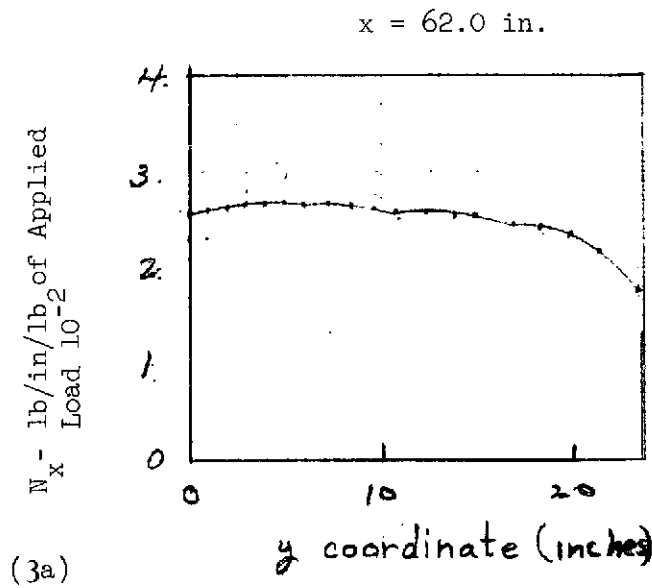
Figure 3 Stress Resultant N_x along x = 62.0 in. and x = 72.0 in. (skin only).

NØ 1A/4STIF/LS9/L2/G11/BC2/SJ2
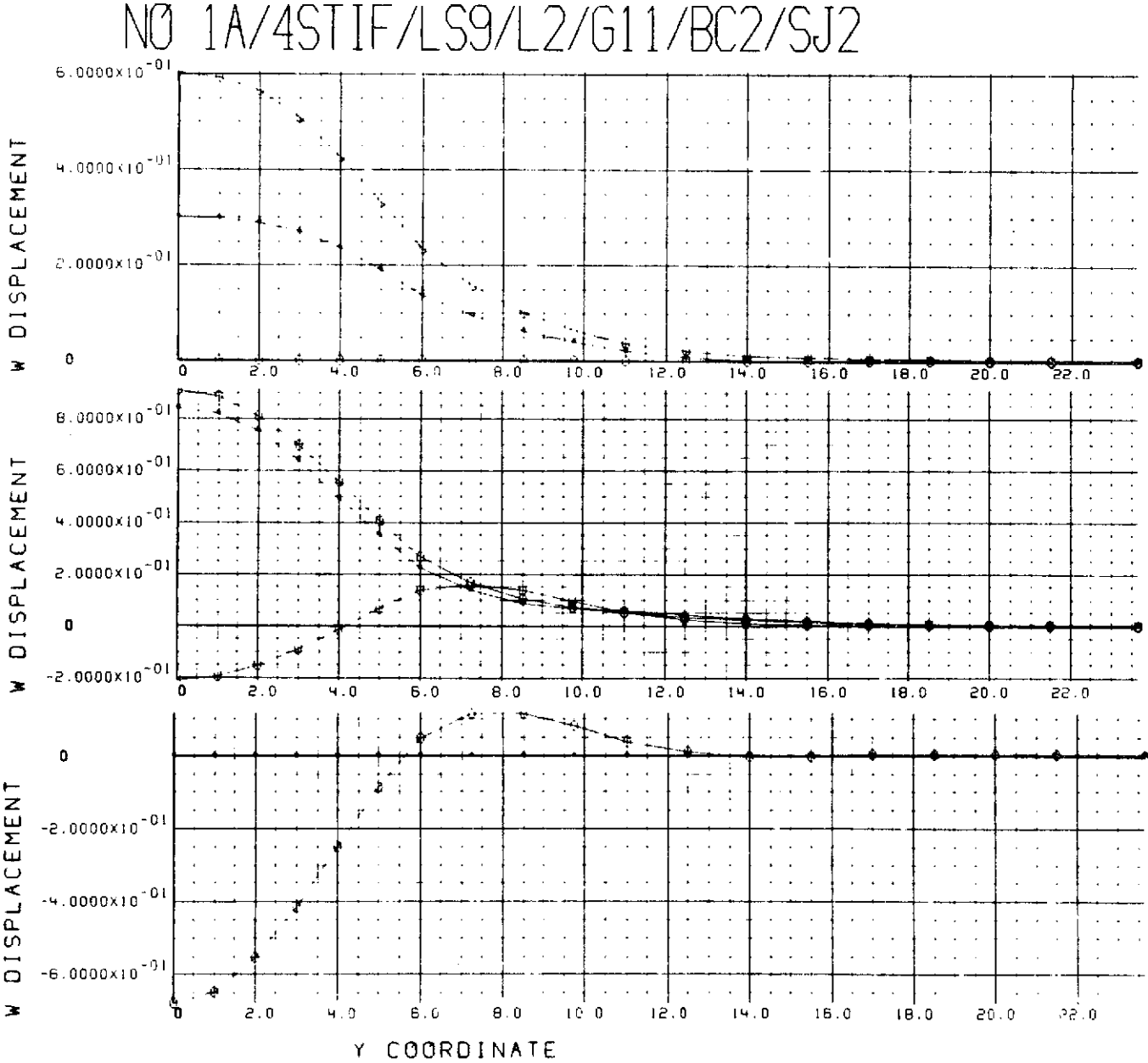
Figure 4   Buckle Mode along Various Axial Locations

NØ 1A/4STIF/LS9/L2/G11/BC2/SJ2

Bifurcation Buckling Load = 374,000 #
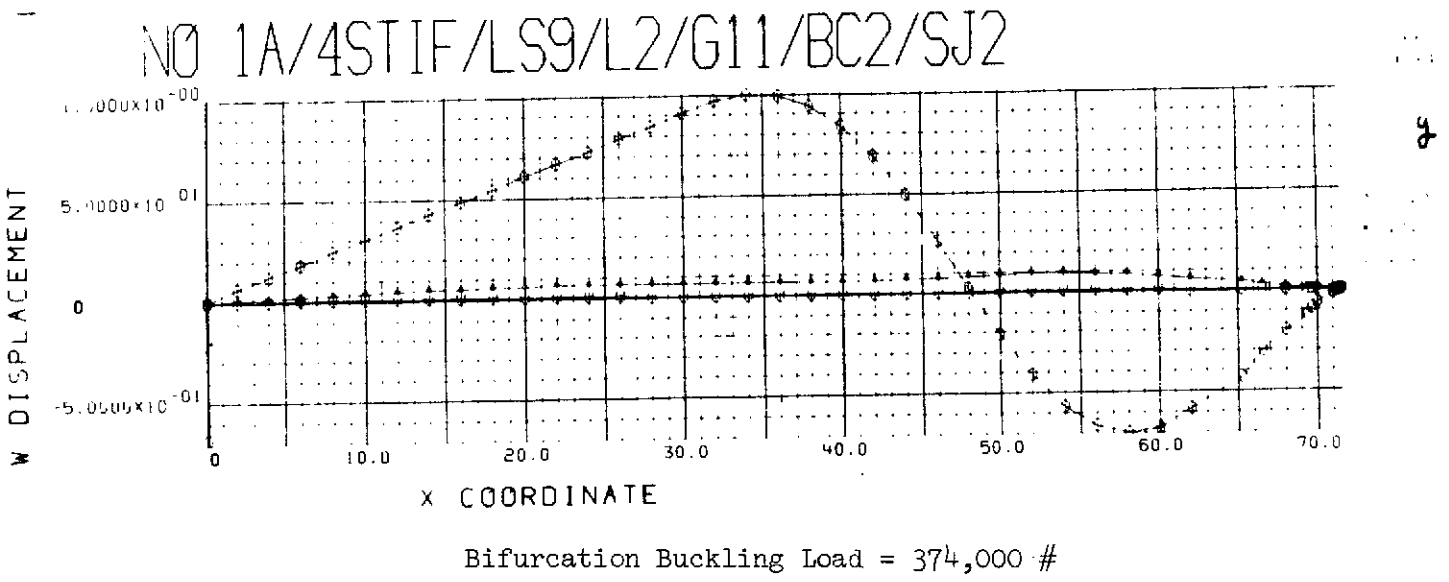
Figure 5   Buckle Mode along Various Transverse Locations

Appendix G

EM B1-M2-4

STAGS ANALYSIS OF UNIFORM
AND CONCENTRATED LOAD PANELS

ENGINEERING MEMORANDUM

TITLE: ANALYSES OF THE CONCENTRATED LOAD AND UNIFORM LOAD PANELS WITH THE STAGS COMPUTER CODE	EM NO: B1-M2-4 REF: DATE: 3 January 1972
AUTHORS: Perry Stern	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

The primary purpose was to determine the buckling load (linear bifurcation buckling) of four beryllium panels. These panels are designated as:

● Concentrated Load Panel
● Concentrated Load Subpanel
● Uniform Load Panel
● Uniform Load Subpanel

and details of their geometry are shown in Figures 1 through 8. The stability analysis was performed with the STAGS (Structural Analysis of General Shells) computer program. This program also gives the prebuckling stress distribution. Therefore, both a stress and stability analysis are reported in this EM.

RESULTS

STAGS computes the bifurcation load (eigenvalue), buckle mode (eigenvector) and prebuckling stress distribution. Summarized results of these quantities for the four panels are presented in the Discussion section. Following are the buckle loads obtained by STAGS for the four panels.

Panel Designation	Buckle Load
Concentrated Load Panel	2.0 x 350,000 lb
Concentrated Load Subpanel	3.5 x 250,000 lb
Uniform Load Panel	1.5 x 7,200 lb/in
Uniform Load Subpanel	3.8 x 7,200 lb/in

DISCUSSION

This discussion is divided into three sections, General, Concentrated Load Panels, and Uniform Load Panels. The General Section includes a description of STAGS and its output

as well as the manner in which the panels are modeled and information common to all panels. The stress and stability analysis of the two concentrated load panels are given in the Concentrated Load Panels Section while the analysis of the two uniform load panels are given in the Uniform Load Panels Section.

REFERENCES

F. A. Brogan, B. O. Almroth, and F. Zele "User's Manual for the STAGS Computer Code" LMSC-D032008, October 7, 1971.

GENERAL

Details of the STAGS computer program may be found in the user's manual previously referenced. The program can solve both linear and nonlinear (geometrical and material) shell structures subjected to mechanical and thermal loads. The numerical results obtained for this report uses the bifurcation buckling option of the program. Since STAGS utilizes finite difference expressions for deformation in the energy it is necessary to discretize the problem domain. For the panels under investigation mesh lines correspond to constant x and y coordinate lines. The unknowns are the normal displacements (W) at the grid points and the two tangential displacments (U in x direction, V in y direction) at the center of elements defined by adjacent mesh lines (the program prints and plots the tangential displacements at node points). Figure 9a shows a typical flat panel with mesh lines and positive deformation components. Figure 9b shows positive stress resultants and couples. It is noted that the deformations and stress resultants are computed at the reference surface (Z = 0). To compute stresses at outer and inner surfaces from the stress resultant ($N = N_x$, N_y, or N_{xy}) and stress couple ($M = M_x$, M_y, or M_{xy}) for a panel with the same material through its thickness the following equation can be used:

$$\sigma = \frac{N}{t} \pm \frac{6\bar{M}}{t^2} \qquad (1)$$
$$\bar{M} = M - Nz$$

in which t is the panel thickness and z is the distance from the reference surface to the panel middle surface. In all problems analyzed the middle surface of the beryllium panel was chosen as the reference surface.

Since all of the panels are to be tested at 600°F, the following mechanical properties (E – Youngs Modulus and γ – Poisson's Ratio) were used in the analysis.

Mechanical Properties

Material	E	γ
Beryllium	37.0×10^6 psi	.06
Titanium	13.1×10^6 psi	.3

At this temperature the yield stresses of beryllium and titanium are 43KSI and 85KSI.

Each panel has an end fitting (see Figures 2 and 7) composed of a layer of titanium and two layers of beryllium. These sections were assumed to be a layered plate in the STAGS modeling. Also, details of the cuts in the titanium were not included since the required number of grid lines would be excessive for a stability analysis. All channel stiffeners were modeled as discrete compact beams and extended two inches into the end fittings. The titanium load fitting shown in Figure 3 was also modeled as discrete beams. All other modeling was handled as if the plate were layered. It is in these regions that the thickness of the entire cross section can be used to compute stresses by Equation 1. The basic thickness of the Concentrated Load Panel is .125" and the thickness of the Uniform Load Panel is 0.11". Note that the Concentrated Load Panel has beryllium doublers (.125 inches thick) as shown in Figure 1. These doublers were modeled with the basic skin as a layered plate.

CONCENTRATED LOAD PANELS

Figure 10 describes the STAGS modeling of the Concentrated Load Panels. Included in this figure are the external dimensions, coordinate system, location of stringers, loading, and boundary conditions. The differences between the subpanel and full panel is its external dimensions and the fact that the beryllium doubler is not cut back. Also one stringer is omitted. Since the subpanel will only be tested to a limit load of 250,000 lb., this load was applied to determine the prebuckling stress distribution. Symmetry allows only one half of panels to be analyzed. This accounts for the symmetry condition along $y = 0$ in Figure 10.

Figures 11 through 16 present the stress resultants and couples for the Concentrated Load Panel (see Figure 1) as a function of the y coordinate for $x = 0$, 10, 20, 30, 40, 50, 60, and 72 inches. Figures 17 and 18 gives the stress resultants and couples along $y = 0$, 2, and 3 inches. Along $y = 0$ the thickness of beryllium is .375 inches, hence, for a stress level of 40 KSI the stress resultant would be 15,000 lb/in (Equation 1). For the 0.125 inch thick material, a stress resultant of 5,000 lb/in corresponds to 40 KSI. From Figure 17, it is seen that Nx is greater than 40 KSI only between $x = 15$ inches and 27 inches. It was felt that this highly stressed region would be relieved by a redistribution of load due to plastic action. It is also seen that the moments are high in the load fitting. Here it is noted that the reference surface is the middle surface of the beryllium skin and Equation 1

should again be applied. Figure 15 shows stress resultants along x = 60 inches and
72 inches. It is seen that the stresses at 72 inches are quite uniform and well
within the design variance of $\overset{+}{-}$ 30 percent.

Figures 19 through 24 present the stress resultants and couples for the Concentrated
Load Subpanel as a function of y for x = 0, 10, 20, 30, 40 and 43 inches. Figures
25 and 26 gives the stress resultants and couples along y = 0, 2 and 3 inches.
These figures show that stresses will not be above 40 KSI for the applied limit
load. Unlike the full panel, the stress distribution for the subpanel at x = 43 inches
(Figure 23) is not uniform. In fact Nx varies from 8.3 KPI to 6.5 KPI.

The STAGS bifurcation analysis gives an eigenvalue of 2.0. Since the applied load
was equivalent to a total load of 350,000 lb for the full panel the critical buckling
load P_{cr} = 350,000 x 2.0 = 700,000 lb. This load would produce stresses well above
yield for the material. Therefore, stability is not a problem area. Buckling
occurs, according to the eigenvector, between the outer stringers and between x = 40
inches and 60 inches as seen in Figure 27. Note that the normal deformation W is a
normalized with respect to one. Here the half wave length of the buckle is about
6 inches in both the x and y directions.

For the Concentrated Load Subpanel the bifurcation buckling analysis gives an
eigenvalue of about 3.2. This corresponds to a total critical load of 250,000 x
3.2 = 800,000 lb. As in the full panel this load corresponds to extremely high elastic
stresses. The main point is that the panel should not buckle at an applied load of
250,000 lbs. Figure 27 shows the buckle mode for this panel. Again buckling occurs
between the outer two stringers starting at about x = 10 inches and ending at 30
inches. Again the half wave length of the buckle is about 6 inches in both the
x and y directions.

UNIFORM LOAD PANELS

A discussion on the analysis of the Uniform Load Panel and Uniform Load Subpanel
is presented in this section. Figure 28 gives the STAGS modeling of the two panels
from the standpoint of stringer location panel dimensions, end fitting and
boundary conditions. It is noted here as in the Concentrated Load Panel analysis
that all details of the end fitting were not modeled such as the cuts in the titanium

plate. As seen from Figure 28 the major difference between the two panels is the
external dimensions. Because of symmetry only one quarter of the full panel was
modeled. This accounts for the symmetry boundary conditions along x = 0 and y = 41
inches and 21 inches.

STAGS results of the axial stress resultants (Nx) prestress, buckle mode, and
buckle load are presented on Figure 29 for the Uniform Load Panel and Figure 30
for the Uniform Load Subpanel. The maximum Nx in the beryllium skin (t =.11 inches)
is 4,600 #/in located at x = 12 inches, y = 1.75 inches of the Uniform Load Panel
(Figure 29). This corresponds to a stress of 41,800 psi with an ultimate applied
load of 7,200 #/in at the end fitting. Thus at limit load (ultimate/1.4) no
yielding will occur in either panels. Nx along x = 41.0 inches varies from
    -4000 to -3850 #/in for the Uniform Load Panel while Nx along x = 21 inches
varies from -3,500 to -3,200 #/in for the Uniform Load Subpanel. This difference
in Nx between the two panels is due to the difference in bending.

Bifurcation buckling results also indicate that the panels will accept an ultimate
load of 7,200 lb/in. For the Uniform Load Panel a critical load factor of 1.53 was
obtained. This implies that the critical axial load (Nx_{cr}) is 1.53 x 7.2 KPI =
110,000 lb/in. Note however that this value may not be reached because of plastic
response of the material. The buckle mode for this panel is a half wave in both the
x and y directions and corresponds to general instability in which the stringers and
plate buckle together.

For the Uniform Load Subpanel a critical load factor of 3.84 was obtained. The
buckle mode for this panel as shown in Figure 30 occurs between stringers and
has a half wave length in both the x and y directions of about 3.75 inches. Along
y = 0 the buckle mode was allowed to be non-symmetric. In comparison, another case
was run in which the buckle mode was restricted to be symmetric about y = 0. In
this case the critical load factor was 5.7 with a similar buckle pattern except
for the condition along y = 0. As in the Uniform Load Panel, stability is not a
problem even up to the ultimate load of 7,200 lb/in.

NAS 8 - 27739

CONCENTRATED LOAD PANEL

CONFIGURATION

SKC201001 Rev.

48.0"

72.0"

Uniform Load Take-Out Fitting (Titanium)

Beryllium Doubler & Splice Plate (Front & Back)

Beryllium Panel & Stringers

Beryllium Doubler (Back Side Only)

Lateral Stiffener (Back Side Only)

Concentrated Load Fitting (Titanium) (Front & Back)

Fig. 1.

NAS8-27739

CONCENTRATED LOAD PANEL
UNIFORM LOAD TAKE-OUT FITTING

.125 Be Sheet

.125 Be Stiffener

72"

.75

.125 Be Doubler

3/16" Dia Rivets

3/8" Ti Fitting

7/16" AN Bolts

Loading Test Fixture

Fig. 2

FORM LMSC 382 B-2

NAS8-27739

CONCENTRATED LOAD PANEL (Cont'd)

CONCENTRATED LOAD FITTING (Cont'd)

CUMULATIVE RIVET LOADING	
① No. OF RIVETS EFFECTIVE	② LOAD TRANSFER CAPABILITY (KIPS)
92	391
88	375
86	366
70	298
66	281
54	230
48	204
28	119
24	102
0	0

① Number of rivets effective in transferring load from fitting into panel.
② Based on double shear capability = 4260 lbs/rivet.

Fig. 3.

CONCENTRATED LOAD PANEL (Cont'd)

CONCENTRATED LOAD FITTING CONFIGURATION

NAS 8-27739

6AL-4V TITANIUM (Annealed) — MAT'L PROPERTIES @ 600°F.

$F_{tu} = 96$ ksi

$F_{ty} = 80$ "

$F_{cy} = 85$ "

$E = 13.1 \times 10^6$ psi

WELDED ASSY

.125"× 3" Be [

.125 Be Sheet

Wide Be Doubler on Back side Only.

Titanium Fitting (Front & Back)

Lateral Stiffener Back side only (Titanium)

4.0"   4.0"   6.0"

Fig 4.

FORM LMSC 362 B-2

NAS 8-27739

CONCENTRATED LOAD TEST SUB-PANEL   SK/201007

CONFIGURATION

Fig. 5

NAS 8-27239

UNIFORM LOAD PANEL — SKJ 20/002

CONFIGURATION

CROSS - SECTION

Fig. 6

NAS 8-27739

UNIFORM LOAD PANEL
END FITTING

.110
Be Sheet

Be Stiffeners

.110 Be
Doubler

80"

.625"
Rivet
Spacing

5/32 Dia
Rivets

.312 Ti
Fitting

7/16" AN Bolts

Loading
Test Fixture

Fig. 7

FORM LMSC 362 B-2

NASB-27739

UNIFORM LOAD SUB-PANEL - SKJ 201004

Titanium Loading Plate
Identical each end.
Configuration same as full
size panel.

Beryllium Panel w/Stiffeners
Cross-section identical
to full size panel.

Beryllium Doublers
Identical each end.
Configuration same as full
size panel.

Fig. 8

NAS8-27739

DESCRIPTION OF COORDINATES, DISPLACEMENT COMPONENTS, AND STRESS RESULTANTS
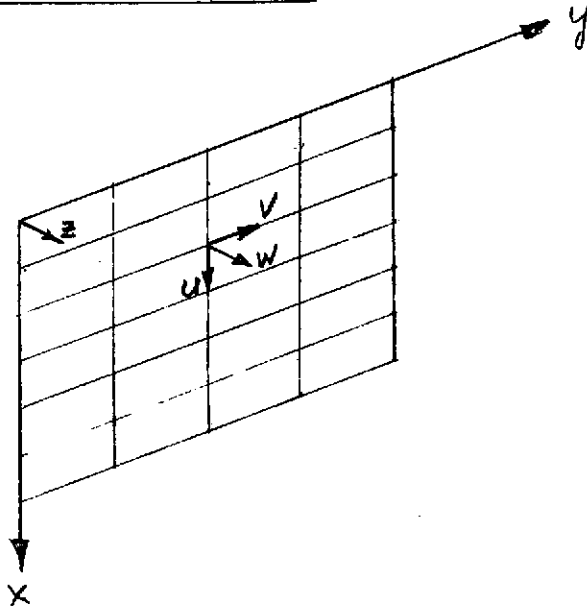
(a) Panel with Mesh, Coordinates, and Positive Displacement Components
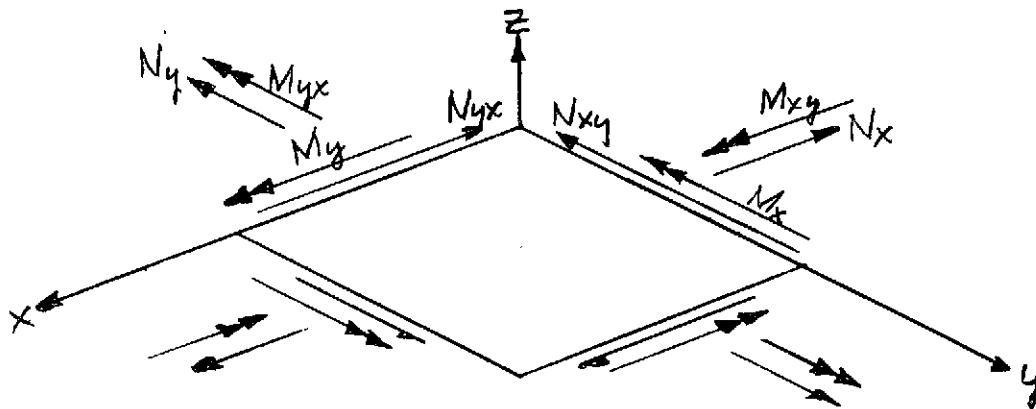
(b) Positive Stress Resultants (N_x, N_y, N_{xy}) and Couples (M_x, M_y, M_{xy})

Fig. 9.

LOCKHEED MISSILES & SPACE COMPANY

STAGS MODELLING

OF CONCENTR. LD. PANELS

Report No. EM # B1-M2-4

Concentrated Load Panel

Concentrated Load Sub Panel

$P_1 P_2 P_3 P_4$

$(W = M_x = N_{xy} = 0)$

42"

73"

Symmetry

Simple Support
$(W = M_y = N_{xy} = N_y = 0)$

$(W = M_y = N_{xy} = N_y = 0)$

10"

1"

$(W = \omega_x = u = N_{xy} = 0)$

23.65

43.0"

17.0"

Channel Stiffener Locations

$y = 5.0, 11.0, 17.0, 23.65$

Applied Load — lbs

y	Ultimate	Limit
0	31,500	22,500
1.0	12,600	9,000
2.0	12,600	9,000
3.0	118,650	84,750

Fig. 10

FORM LMSC 982 B-2

PANEL A/LS15E/L4/G12/BC3/SJ3

U1108/SC4020
0008 0007
03 NOV 71
19Y47Y30

Fig. 11

PANEL A/LS15E/L4/G12/BC3/SJ3

U1108/SC4020
0000 0008
03 NOV 71
13147V31

Fig. 12

PANEL A/LS15E/L4/G12/BC3/SJ3

Fig. 13

PANEL A/LS15E/L4/G12/BC3/SJ3

Fig. 14

FORM LMSC 362 B-2

PANEL A/LS15E/L4/G12/BC3/SJ3

Fig. 15

PANEL A/LS15E/L4/G12/BC3/SJ3

Fig. 16

PANEL A/LS15E/L4/G12/BC3/SJ3

U1109/SC4820
0000 001
03 NOV 71
19169001

Fig. 17

FORM LMSC 352 B-2

PANEL A/LS15E/L4/G12/BC3/SJ3

Fig. 18

CONCENTRATED LOAD MINI PANEL

Fig. 19.

CONCENTRATED LOAD MINI PANEL

Fig. 20

FORM LMSC 382 B-2

CONCENTRATED LOAD MINI PANEL

Fig. 21

Fig. 22

CONCENTRATED LOAD MINI PANEL

Fig. 23

CONCENTRATED LOAD MINI PANEL

U1108/SC4020L
0000 0012
20 NOV 71
15816828

Fig. 24

FORM LMSC 362 B-2

CONCENTRATED LOAD MINI PANEL

Fig. 25

FORM LMSC 362 B-2

CONCENTRATED LOAD MINI PANEL

Fig. 36

FORM LMSC 362 B-2

Fig. 27

Uniform Load Panel

$N_x = 7,200 \ \#/in$

$(W = \omega_x = N_{xy} = 0)$

10"

41"

Symmetry

Simple Support $(W = M_y = N_{xy} = N_y = 0)$

14.5"

Symmetry

Stringer Locations
$y = 0., \ 3.625, \ 7.25,$
$10.875, \ 14.5$

Uniform Load Sub Panel

21."

11."

7.5

Stringer Locations
$y = 0., \ 3.75, \ 7.5$

Fig. 88

Fig. 29

FORM LMSC 382 B-2

Fig. 30

Appendix H

EM B1-M2-5

REXBAT ANALYSIS OF UNIFORM
LOAD TAKE-OUT FITTING

ENGINEERING MEMORANDUM

TITLE:	EM NO: B1-M2-5
REXBAT COMPUTER CODE-ANALYSES OF UNIFORM LOAD TAKE-OUT FITTING	REF:
	DATE: 15 December 1971
AUTHORS: G. S. Fuchigami/G. A. Harter	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Provide an analysis of the discontinuities and stress distribution in the vicinity of the load take-out fitting of the Concentrated Load Panel Drawing SKC 201001, Rev. A.

RESULTS

The results of a finite element analyses performed by means of the REXBAT computer code of the subject structure is presented in this EM.

DISCUSSION

The output from this computer analyses is discussed on Page 2. In general, it showed that the regions of highest stress occur in the basic panel between the stiffeners at the doubler discontinuity. The stress levels (Page 17) are above the elastic range of the material; therefore some plastic behavior and redistribution of stresses can be expected at ultimate load.

TITLE: STRESS ANALYSIS OF THE BERYLLIUM COMPRESS-ION PANEL USING THE REXBAT COMPUTER CODE	EM NO. B1-M2-5 REPORT NO. S/I-384 REF: 62-61
PREPARED BY: G. A. Harter	DATE: 22 Nov. 71
CHECKED BY: D. Faber,	APPROVAL:

INTRODUCTION:

A REXBAT finite element stress analysis has been completed on a section of the stringer stiffened beryllium compression test panel. This study was conducted for the Evaluation of Beryllium for Space Shuttle Components, contract number NAS 8-27739.

The purpose of the REXBAT stress analysis was to determine panel and stringer stress concentrations in the region of the uniform load take-out fitting. This E.M. presents the results of the stress analysis through a series of stress and contour plots generated by post-processors to the REXBAT program.

Method:

The overall dimensions of the complete test panel are 48 inches wide by 72 inches long. Figure 1 is a drawing of the 15.37 inch long section of the structure modeled for REXBAT. This section includes the complete uniform load take-out fitting and doubler. The 15.37 inch cut-off was based on a STAGS*computer stress analysis indicating this to be a region of nearly constant strain in the panel. The axis system is shown with the X-axis along the symmetrical center line of the panel and the Y-axis extending from the center to the panel edge. This axis system is used for specification of plot locations.

The model contains 300 node points. All structural components of the panel were modeled as quadrilateral membrane elements overlayed with triangular bending elements. In total, 498 membrane quadrilaterals and 996 bending triangles are contained in the REXBAT model.

The loading condition used for the analysis was a uniform -0.1 inch X-displacement of the plane at the X = 15.37 station line. Symmetry boundary conditions were used at the panel centerline (Y = 0.0) so that

* Finite difference analysis performed by Perry Stern D/52-33

Prepared by: G. A. Harter	Date 11/22/71	LOCKHEED MISSILES & SPACE COMPANY A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION	Page	Temp.	Perm. 2
Checked by: D. *keiuct*	Date 12/16/71	Title STRESS ANALYSIS OF THE BERYLLIUM COMPRESSION PANEL USING THE REXBAT COMPUTER CODE	Model		
Approved by: *w. j. —/...l. ll.*	Date		Report No. S/I-384		

EM No. B1-M2-5

only a half model of the fitting area was required. A simple support condition was imposed at one of the panel edges (Y = 24.0) and the end of the panel was fixed (X = 0.0).

Figure 2 shows an isometric view of the undeformed structure as generated by the REXBAT internal plot package. The axis system shown corresponds to that of Figure 1.

The initial analysis was run with the beryllium centerline (Y = 0.0) doubler thickness equal to .140 inches. This configuration was updated to a new design thickness of .125 inches. Other component thicknesses remained the same. Two packages of graphical results are presented, one for the .140 centerline doubler thickness and the second for the .125 doubler thickness.

Results:

Figures 3 and 16 show the panel membrane stress distribution at X station 15.37, the line of uniform applied displacement. The average stress is shown by the dashed line and is used as the stress concentration factor (K = 1.0) reference point for interpreting the graphical portion of the corresponding results package.

Figures 4 through 10 and 17 through 23 show the panel stress concentration in the beryllium sheet at the specified X station cut lines. The plus (+) or minus (-) after the X station number indicates which quadrilateral element stress concentrations were plotted at the specified station number. For example, Figure 4 is the panel stress concentration for the X = 12.37- station line. This means that the quadrilaterals on the minus (-) side of this station yielded the stress concentrations plotted for the respective cut line node points (see figure 1, X station = 12.37 node 10 for an example of the plus (+) and minus (-) directions). The stations were selected to show maximum stress concentration variations, generally, where the overall panel thickness changed.
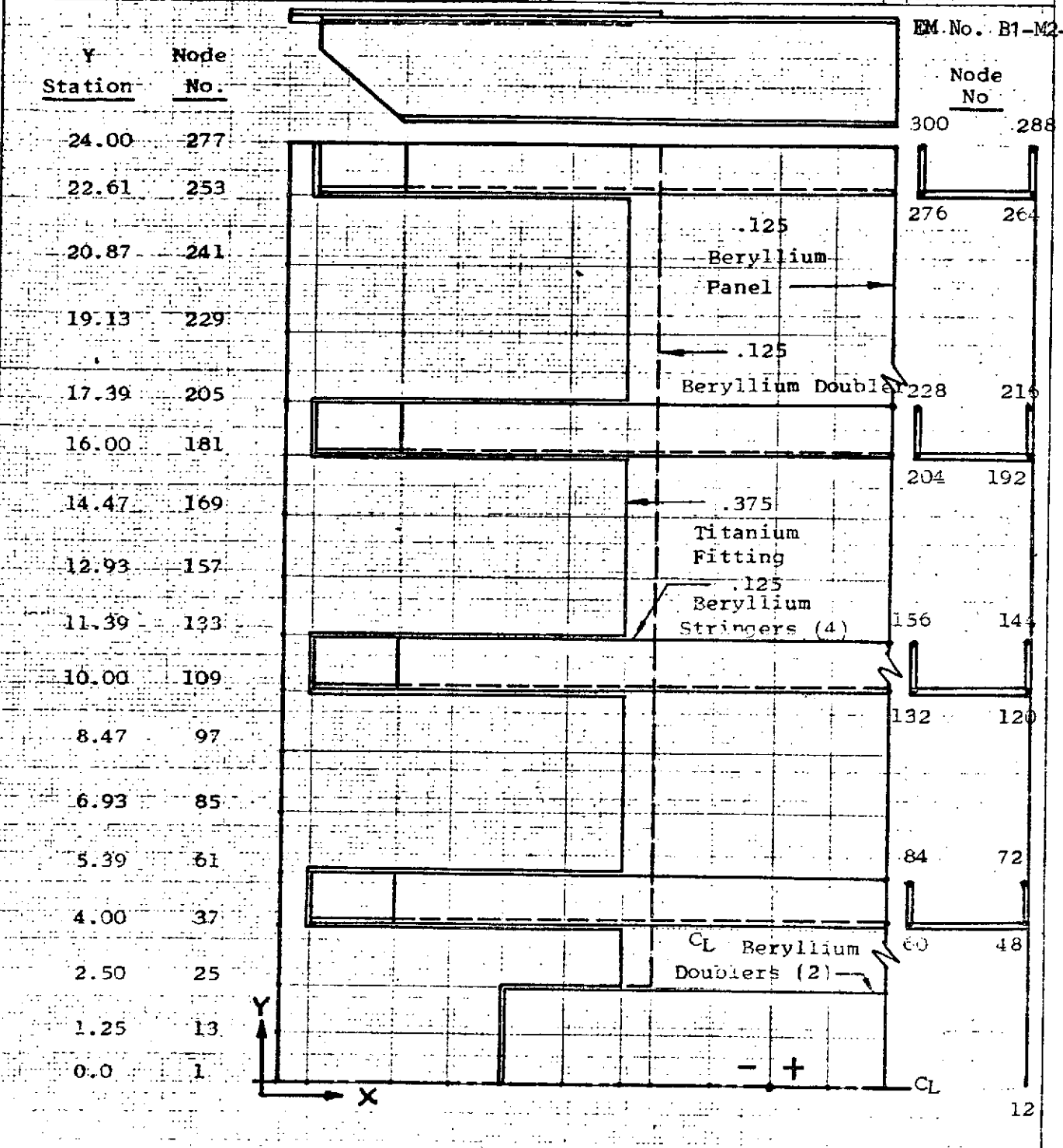
EM No. B1-M2-5

Figures 11 through 14 and 24 through 27 show the stress concentration

through four cut lines on the "C" section stringer at the Y = 10.0

station line. This stringer was selected for plotting because it was
in the region of highest stress concentration for the applied loading con-
dition. The sketches above Figures 11 and 24 are examples of node point
locations on the cross section for the plotted values. The plots show
that the top portion of this stringer carries very little load in the
fitting area. Mid-panel stability factors must, therefore, be used as
a justification for its inclusion into the design.

Figures 15 and 28 are contour plots of the X stress concentration factor
in the beryllium panel. Stringers and doublers are traced in to show
the orientation of the panel. Stress concentration values are shown
in the associated legend and correspond to the numbered and lettered lines
on the plot. Since the contour plotting program averages stresses across
node points, jump stress variations (i.e. due to thickness changes) are
spread over the adjacent quadrilateral elements. Because of this
averaging characteristic the peak panel stress concentration of 1.17
is only shown in the cut plot presentation.

The decrease in the centerline doubler thickness from .140 to .125
increased the panel stress in the beryllium sheet by 2 percent where
the sheet is overlapped by the doubler (Y = 0.0—2.5, X = 5.62—15.37).
The sheet stress was reduced by 4 percent in the area from the end of
the doubler to the end of the panel (Y = 0.0—2.5, X = 0.0—5.62). The
peak and average stress concentrations remained essentially the same over
the remainder of the sheet for both thicknesses using the applied uniform
displacement loading condition.

It should be noted that the present model does not take into account
the eccentricity between the beryllium panel and the uniform load
take-out fitting. Assuming the applied average stress to equal 40000 psi
the extreme fiber stress in the titanium fitting due to membrane and
bending forces could reach 100,000 psi at its peak point near the corner
of the panel (station lines X = 0.0, Y = 24.0).

Figure 1. REXBAT STRUCTURAL MODEL

EM.No. B1-M2-5

Y Station / Node No.

Y Station	Node No.
24.00	277
22.61	253
20.87	241
19.13	229
17.39	205
16.00	181
14.47	169
12.93	157
11.39	133
10.00	109
8.47	97
6.93	85
5.39	61
4.00	37
2.50	25
1.25	13
0.0	1

.125 Beryllium Panel

.125 Beryllium Doubler

.375 Titanium Fitting

.125 Beryllium Stringers (4)

C_L Beryllium Doublers (2)

Node No: 300, 288, 276, 264, 228, 216, 204, 192, 156, 144, 132, 120, 84, 72, 60, 48, 12

Node No.	X Station
1	0.0
2	0.75
3	2.90
4	4.26
5	5.62
6	7.12
7	8.62
8	9.37
9	10.87
10	12.37
11	13.87
12	15.37

EM No. B1-M2-5

FIGURE 2

BERYLLIUM COMPRESSION PANEL - QUAD ELEMENTS

EM No. B1-M2-5

Fig. 3 PANEL STRESS . X= 15.37-
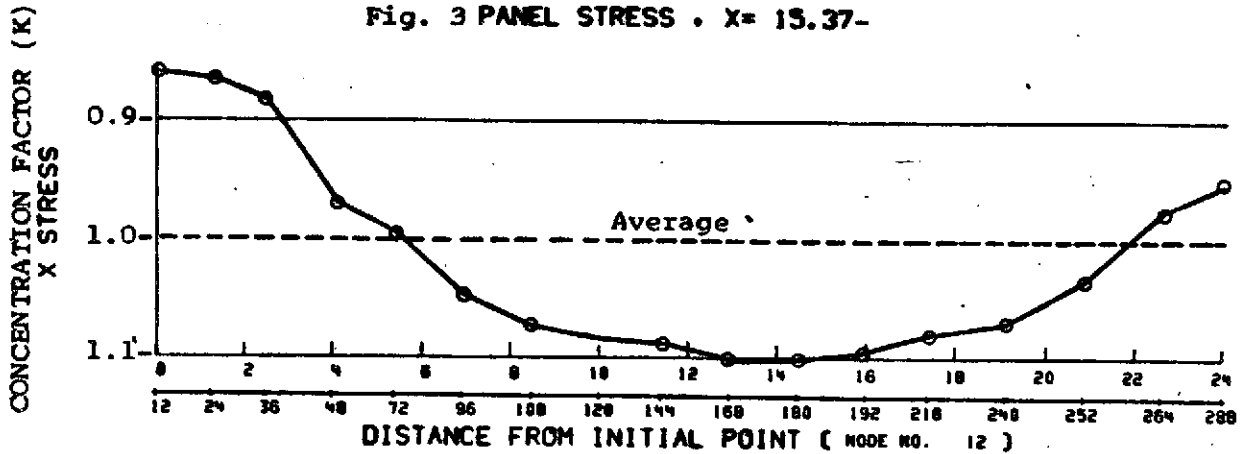
Fig. 4 PANEL STRESS . X= 12.37-
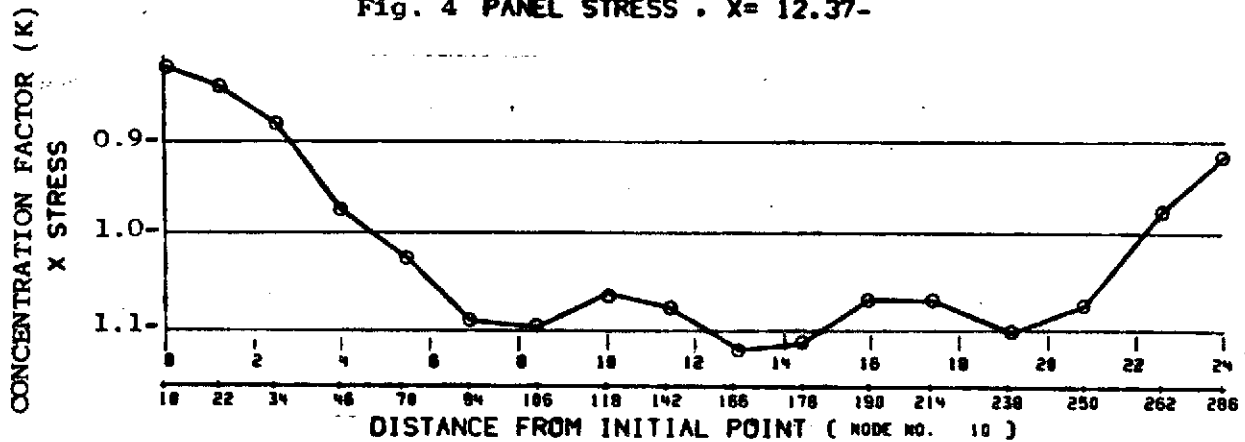
Fig. 5 PANEL STRESS . X= 9.37+

.140 Centerline Doubler Thickness   H-7

FORM LMSC 362 B-2

EM No. B1-M2-5

Fig. 6 PANEL STRESS . X= 8.62+
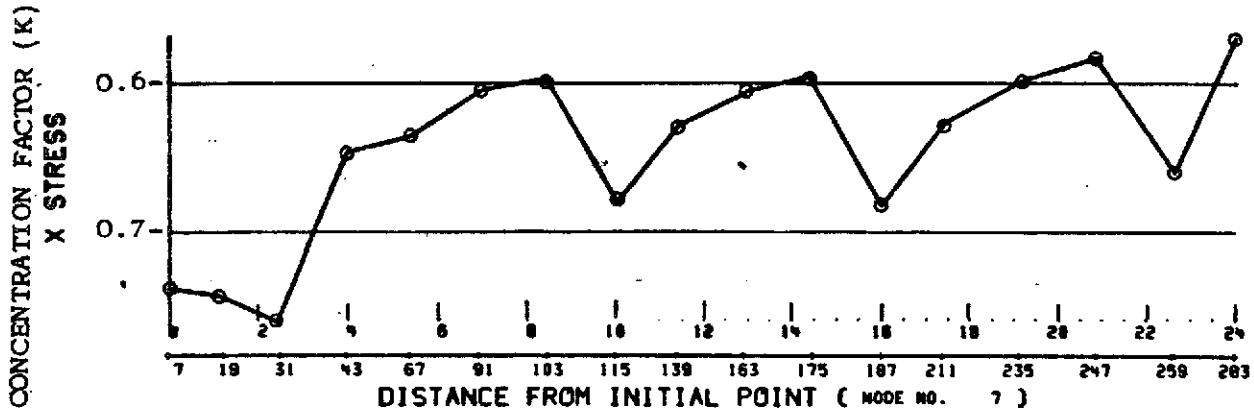
Fig. 7 PANEL STRESS . X= 7.12+

Fig.8 PANEL STRESS . X= 4.26+

.140 Centerline Doubler Thickness   H-8

EM No. B1-M2-5

Fig.9 PANEL STRESS . X= .75+

Fig. 10   PANEL STRESS . X= 0.0+

.140 Centerline Doubler Thickness   H-9

EM No. B1-M2-5

132   156
120   144
To Panel ℄

Fig. 11   Y=10. STIFFENER STRESS . X= 15.37-

CONCENTRATION FACTOR (K) X STRESS

DISTANCE FROM INITIAL POINT (NODE NO. 144)

Fig. 12   Y=10. STIFFENER STRESS . X= 9.37+

CONCENTRATION FACTOR (K) X STRESS

DISTANCE FROM INITIAL POINT (NODE NO. 140)

.140 Centerline Doubler Thickness   H-10

EM No. B1-M2-5

Fig. 13   Y=10. STIFFENER STRESS . X= 7.12+

DISTANCE FROM INITIAL POINT (NODE NO. 138)

Fig. 14   Y=10. STIFFENER STRESS . X= 2.90+

DISTANCE FROM INITIAL POINT (NODE NO. 135)

.140 Centerline Doubler Thickness   H-11

EM No. B1-M2-5

FIGURE 15
BERYLLIUM PANEL X STRESS CONCENTRATION
CONTOUR PLOT

X Stress
Concentration
Legend

3	1.131
4	1.101
5	1.071
6	1.042
7	1.012
8	.982
9	.952
A	.923
B	.893
C	.863
D	.833
E	.804
F	.774
G	.744
H	.714
I	.685
J	.655
K	.625
L	.595
M	.565
N	.536
O	.506
P	.476
Q	.446

.140 Centerline Doubler Thickness

H-12

Prepared by: G. A. Harter	Date 11/22/71	LOCKHEED MISSILES & SPACE COMPANY A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION	Page	Temp.	Perm. 12
Checked by: E. Lentz	Date 12/16/71	Title STRESS ANALYSIS OF THE BERYLLIUM COMPRESSION PANEL USING THE REXBAT COMPUTER CODE	Model		
Approved by:	Date		Report No. 62-61/S/I384		

EM No. B1-M2-5

Fig. 16 PANEL STRESS . X= 15.37-

Fig. 17 PANEL STRESS . X= 12.37-

Fig. 18 PANEL STRESS . X= 9.37+

.125 Centerline Doubler Thickness

H-13

EM No. B1-M2-5

Fig.19 PANEL STRESS . X= 8.62+
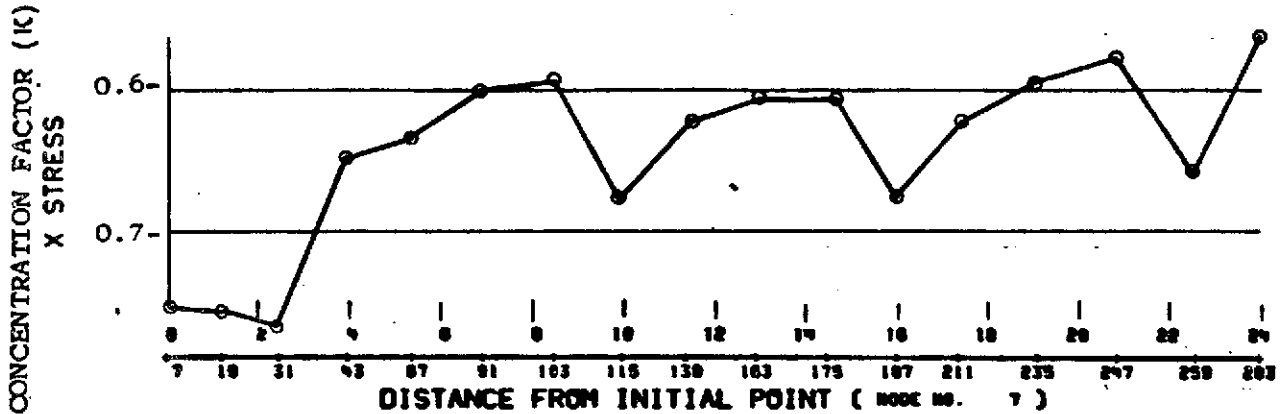
Fig.20 PANEL STRESS . X= 7.12+
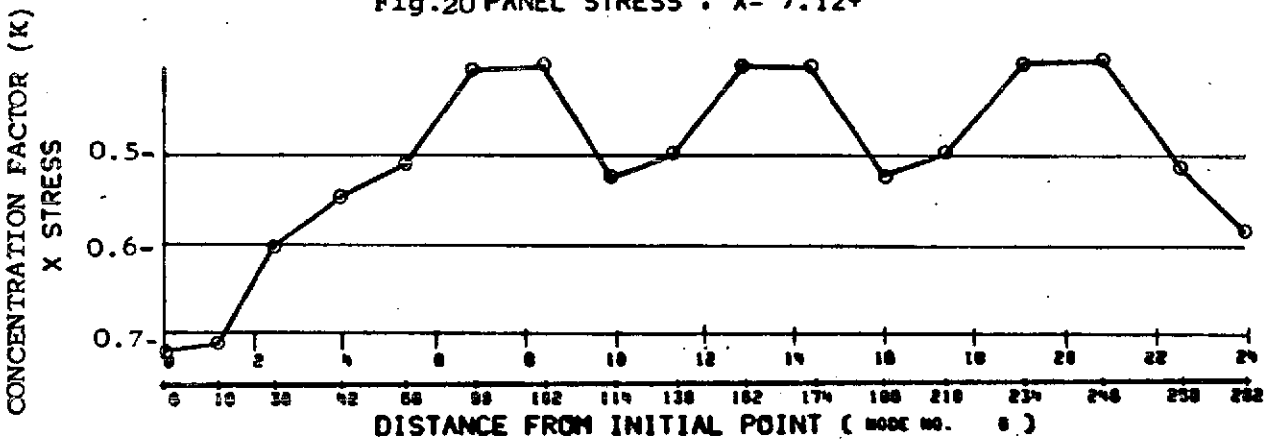
Fig.21 PANEL STRESS . X= 4.26+
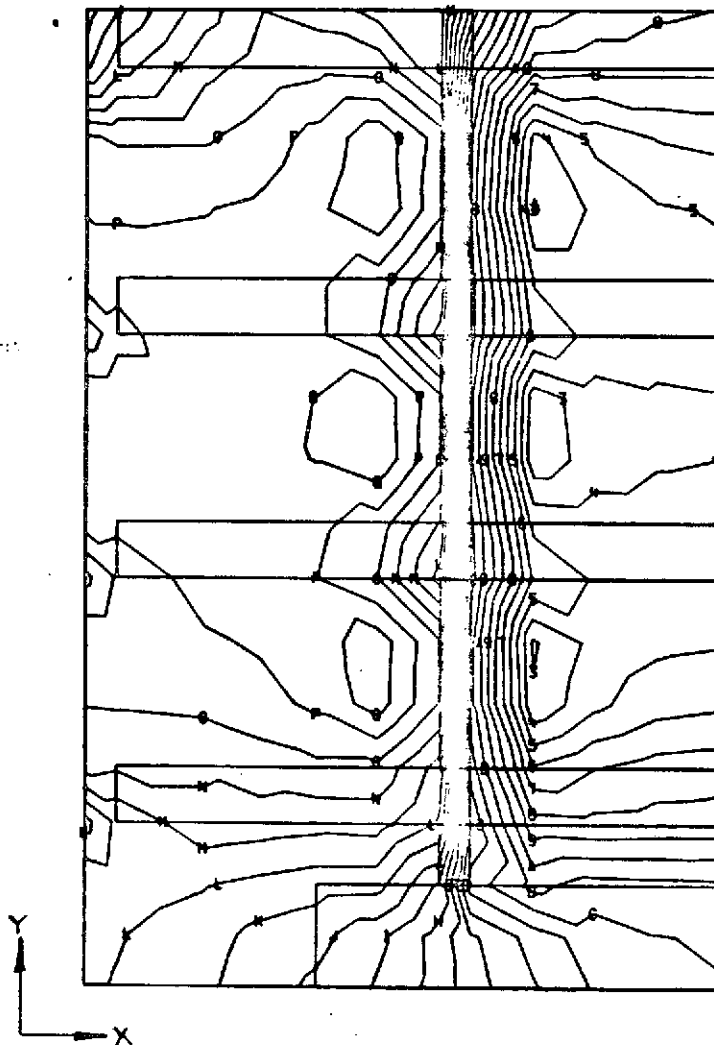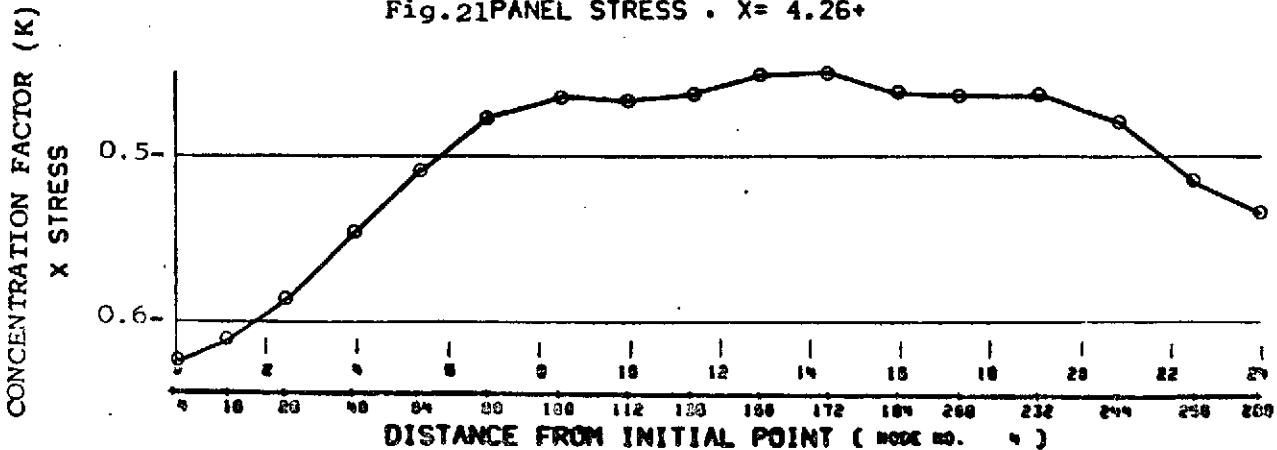

.125 Centerline Doubler Thickness

H-14

Prepared by: G. A. Harter	Date 11/22/71	LOCKHEED MISSILES & SPACE COMPANY A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION	Page	Temp.	Perm. 14
Checked by: E. Roberts	Date 12/16/71	Title STRESS ANALYSIS OF THE BERYLLIUM COMPRESSION PANEL USING THE REXBAT COMPUTER CODE	Model		
Approved by:	Date		Report No. 62-61/S/I384		

EM No. B1-M2-5

Fig.22 PANEL STRESS . X= .75+

Fig. 23   PANEL STRESS . X= 0.0+

.125 Centerline Doubler Thickness

H-15

EM No. B1-M2-5

Fig. 24   Y=10. STIFFENER STRESS . X= 15.37-
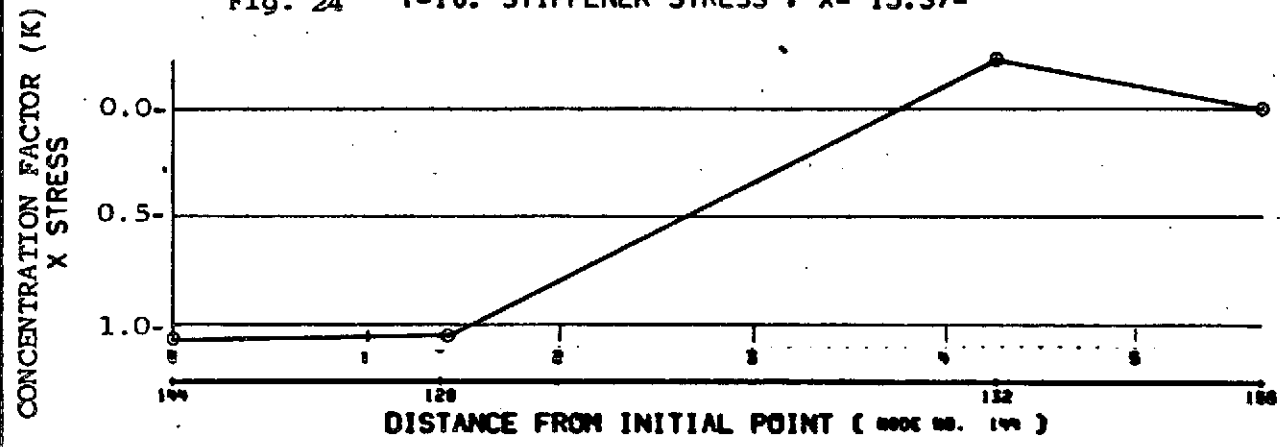
Fig. 25 Y=10. STIFFENER STRESS . X= 9.37+

.125 Centerline Doubler Thickness

H-16

EM No. B1-M2-5

Fig. 26   Y=10. STIFFENER STRESS . X= 7.12+

Fig. 27   Y=10. STIFFENER STRESS . X= 2.90+

.125 Centerline Doubler Thickness   H-17

EM No. B1-M2-5

FIGURE 28

BERYLLIUM PANEL X STRESS CONCENTRATION

CONTOUR PLOT
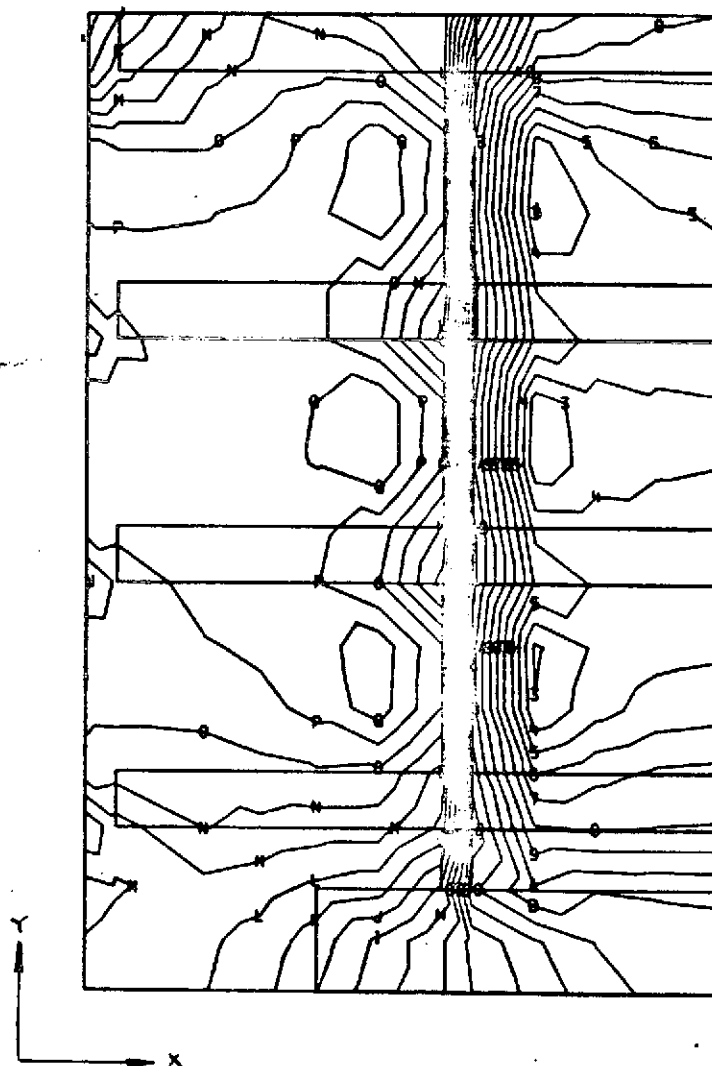
	X Stress Concentration Legend
3	1.126
4	1.096
5	1.067
6	1.037
7	1.008
8	.978
9	.948
A	.919
B	.889
C	.859
D	.830
E	.800
F	.771
G	.741
H	.711
I	.682
J	.652
K	.622
L	.593
M	.563
N	.533
O	.504
P	.474
Q	.445

.125 Centerline Doubler Thickness   H-18

Appendix I

EM B1-M2-6A

STRUCTURES COMPONENT TEST
REQUIREMENTS — SKJ 201004,
SKJ 201007 AND TRUSS COMPONENT

LOCKHEED MISSILES & SPACE COMPANY

ENGINEERING MEMORANDUM

TITLE: STRUCTURAL COMPONENT TEST REQUIREMENTS UNIFORM LOAD TEST PANEL SKJ 201004, CONCENTRATED LOAD TEST PANEL SKJ 201007, AND TRUSS COMPONENT	EM NO: B1-M2-6A
	REF: (Rev. A, 2-23-72)
	DATE: 15 December 1971
AUTHORS: G. S. Fuchigami	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Prepare a test requirements document delineating the procedure to be followed in testing the component test articles at LMSC.

RESULTS

The procedure for testing the uniformly loaded sub-panel, the concentrated load sub-panel, and the truss component are detailed in this EM.

DISCUSSION

Testing of sub-scale components of compression panels and of beam components at LMSC is a contractual requirement. This test requirements document describes in detail the procedures to be followed in the testing of the Uniform Load Test Sub-Panel SKJ 201004, the Concentrated Load Test Sub-Panel SKJ 201007, and the truss component. After completion of the testing, this document will provide the guidelines to delineating the test requirements for the MSFC panel tests.

REVISION A

Revision A reflects the following changes:

    a.   Truss component added in the Title, Results and Discussion.

    b.   Appendix C - Truss Component Test added.

    c.   Two room temperature tests added to the testing of the uniform load test panel SKJ 201004.

    d.   Two room temperature tests added to the testing of the concentrated load test panel SKJ 201007.

    e.   The second paragraph under Discussion deleted.

    f.   Figures 2 and 4 revised so that the strains due to temperature can be stabilized prior to application of load.

APPENDIX A - UNIFORM LOAD TEST PANEL SKJ 201004

This document defines the detail requirements and procedures for the structural component testing to be performed per the requirements of this contract. The test panel is shown on SKJ 201004 and the general test setup is shown on Fig. 1.

Load Requirements

The following tests are to be conducted in the sequence shown:
1. Room temperature test to 50 percent limit load.
2. Room temperature test to 100 percent limit load.
3. Elevated temperature test to 50 percent limit load.
4. Elevated temperature test to 100 percent limit load.
5. Elevated temperature test to 140 percent limit load, hold for ten seconds, and continue loading to failure.

The test panel and test data must be examined between each test for anomolies in the recorded data or incipient failures in the test panel.

Two independent methods of reading loads shall be used. Continuous recording of all loads and temperatures during loading periods is required. Loading fixtures shall be designed or counterbalanced so no additional weight is applied to the panel and to minimize damage to the panel at failure. Because of the stiffness of this beryllium material, adequate safety precautions must be taken to protect personnel from possible fragmentation at failure.

Instrumentation Requirements

The panel shall be instrumented with strain gages and thermocouples as shown on SKJ 201004. Continuous data readout is required during all loading periods. For purposes of instrumentation calibration no more than 25 percent of any limit loading condition may be applied to the test panel. All instrumentation shall be calibrated before each test loading and rechecked at zero load after each test. Dwell periods at limit, ultimate, or other loads should normally not exceed ten seconds to provide for instrumentation stabilization and data readout.

Test Procedure

The load and temperatures shall be applied to the test panel per Figure 2. In the event that premature failure may be imminent (visual, audible, or anomalies in instrumentation readout) the test is to be aborted immediately. Resolution of the problem (if any) must be accomplished before continuing. Adequate safety precautions must be emphasized at all times.

Liaison, Photos, Reports

All test setups will be reviewed by the Program Manager and/or the Structures Engineer prior to testing. These same person(s) shall be present during the testing.

Photographic documentation shall be provided as follows:
   a. Still (color) photographs of the test setup and test specimen.
   b. Still (color) photographs of the test specimen after each test.

A test report, documenting the entire testing shall be submitted to the Program Manager (A. Trapp) within 20 days after completion of the tests.

Structural Component Test Requirements

EM No. B1-M2-6A
(Rev. A, 2-23-72)

Uniform Load Test Panel SKJ201004

$$P_{Limit} = 514.0 \text{ lbs/in}$$
$$= 78,300 \text{ lbs}$$

$$P_{Ultimate} = 7200 \text{ lbs/in}$$
$$= 110,000 \text{ lbs}$$

Test Temperatures:
Rm. Temp.
600°F

Side Fillings
See SKJ201004

Notes:
1. End fixtures must be capable of uniform loading on test panel.

2. Side fixtures must be maintained in-plane throughout testing.

Test Set-up
Fig. 1.

EM No. B1-M2-6A
(Rev. A, 2-23-72)

STRUCTURAL COMPONENT TEST REQUIREMENTS

UNIFORM LOAD TEST PANEL   SKJ 201004

TIME IN SECONDS

TIME-PHASED LOADING

Figure 2

APPENDIX B - CONCENTRATED LOAD TEST PANEL SKJ 201007

This document defines the detail requirements and procedures for the structural component testing to be performed per the requirements of this contract. The test panel is shown on SKJ 201007 and the general test setup is shown on Fig. 3.

Load Requirements

The following tests are to be conducted in the sequence shown:
1. Room temperature test to 50 percent limit load.
2. Room temperature test to 100 percent limit load.
3. Elevated temperature test to 50 percent limit load.
4. Elevated temperature test to 100 percent limit load.
5. Elevated temperature test to 140 percent limit load, hold for ten seconds, continue loading to failure.

The test panel and test data must be examined between each test for anomalies in the recorded data or incipient failures in the test panel.

Two independent methods of reading loads shall be used. Continuous recording of all loads and temperatures during loading periods is required. Loading fixtures shall be designed or counterbalanced so no additional weight is applied to the panel and to minimize damage to the panel at failure. Because of the stiffness of this beryllium material, adequate safety precautions must be taken to protect personnel from possible fragmentation at failure.

Instrumentation Requirements

The panel shall be instrumented with strain gages and thermocouples as shown on SKJ 201007. Continuous data readout is required during all loading periods. For purposes of instrumentation calibration no more than 25 percent of any limit loading conditions may be applied to the test panel. All instrumentation shall be calibrated before each test loading and rechecked at zero load after each test. Dwell periods at limit, ultimate, or other loads should normally not exceed ten seconds to provide for instrumentation stabilization and data readout.

Test Procedure

The load and temperatures shall be applied to the test panel per Figure 4. In the event that premature failure may be imminent (visual, audible, or anomalies in instrumentation readout) the test is to be aborted immediately. Resolution of the problem (if any) must be accomplished before continuing. Adequate safety precautions must be emphasized at all times.

Liaison, Photos, Reports

All test setups will be reviewed by the Program Manager and/or the Structures Engineer prior to testing. These same person(s) shall be present during the testing.

Photographic documentation shall be provided as follows:
    a. Still (color) photographs of the test setup and test specimen.
    b. Still (color) photographs of the test specimen after each test.

A test report, documenting the entire testing shall be submitted to the Program Manager (A. Trapp) within 20 days after completion of the tests.
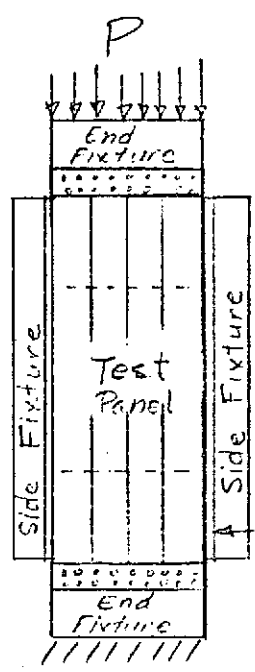
EM No. B1-M2-6A
(Rev. A, 2-23-72)

STRUCT. COMPONENT TEST REQ'MENTS

CONCENTRATED LOAD SUB-TEST PANEL SKJ 201007

Personnel Safety Shield

P

Concentrated Load Fitting

Side Fittings
See SKJ 201007

TEST PANEL

SIDE FIXTURE

SIDE FIXTURE

END FIXTURE

P_{Limit} = 182,000 lbs

$P_{Ultimate}$ = 255,000 lbs.

Test Temperatures:
Rm. Temp.
600° F.

Notes: 1. Load P must be applied over the complete end surface of the concentrated load fitting.

2. End fixture must be capable of uniform loading on test panel.

3. Side fixtures must be maintained in-plane throughout testing.

TEST SET-UP

Fig. 3

EM No. B1-M2-6A
(Rev. A, 2-23-72)

STRUCTURAL COMPONENT TEST REQ'MENTS

CONCENTRATED LOAD SUB-TEST PANEL SKJ201007

Ultimate Load 255,000 lbs

Limit Load 182,000 lbs.

(600°F)

Load

TEMPERATURE

TIME IN SECONDS

TIME-PHASED LOADING

Figure 4

FORM LMSC 382 B-2

APPENDIX C - TRUSS COMPONENT TEST

This document defines the detail requirements and procedures for the structural testing of the truss component to be performed per the requirements of this contract. The general setup is shown on Fig. 5.

Load Requirements

The following tests are to be conducted in the sequence shown:

1. Room temperature test to 50 percent limit load.
2. Room temperature test to 100 percent limit load.
3. Room temperature test to 140 percent limit load, hold for ten seconds, continue loading to failure.

The test beam and test data must be examined between each test for anomalies in the recorded data or incipient failures in the test beam.

Two independent methods of reading loads shall be used. Continuous recording of all loads and temperatures during loading periods is required. Loading fixtures shall be designed or counterbalanced so no additional weight is applied to the panel and to minimize damage to the panel at failure. Because of the stiffness of this beryllium material, adequate safety precautions must be taken to protect personnel from possible fragmentation at failure.

Instrumentation Requirements

The panel shall be instrumented with strain gages as shown on Fig. 5. Continuous data readout is required during all loading periods. For purposes of instrumentation calibration no more than 25 percent of any limit loading conditions may be applied to the test panel. All instrumentation shall be calibrated before each test loading and rechecked at zero load after each test. Dwell periods at limit, ultimate, or other loads should normally not exceed ten seconds to provide for instrumentation stabilization and data readout.

Test Procedure

The load shall be applied to the test beam at a rate of approximately 2 percent limit load per second. In the event that premature failure may be imminent

(visual, audible, or anomalies in instrumentation readout) the test is to be aborted immediately. Resolution of the problem (if any) must be accomplished before continuing. Adequate safety precautions must be emphasized at all times.

Liaison, Photos, Reports

All test setups will be reviewed by the Program Manager and/or the Structures Engineer prior to testing. These same person(s) shall be present during the testing.

Photographic documentation shall be provided as follows:

   a. Still (color) photographs of the test setup and test specimen.
   b. Still (color) photographs of the test specimen after each test.

A test report, documenting the entire testing shall be submitted to the Program Manager (A. Trapp) within 20 days after completion of the tests.

NAS 8-27739

TEST CONFIGURATION

BERYLLIUM BEAM

Braze Area

A

A

26 holes each side on 3/4" centers as shown for #6 Monel rivets.

Section A-A

Braze

3.0 × .125 [
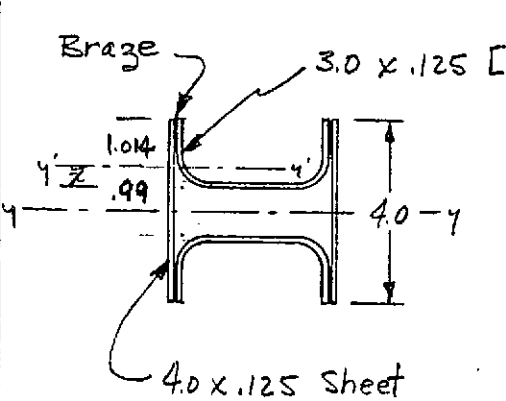
$$\begin{cases} A = .663 \text{ in}^2 \\ I_{yy} = .130 \text{ in}^4 \\ \bar{x} = .436 \text{ in} \end{cases}$$

4.0 × .125 Sheet

$$A = 2(4.0)(.125) + 2(.663) = 2.326 \text{ in}^2$$

$$I_{y\cdot y} = (2)\frac{.125(4.0^3)}{12} + (2)(.663)(.99^2) = 2.63 \text{ in}^4$$

$$\frac{I}{c} = \frac{2.63}{2} = 1.315 \text{ in}^3$$

$$\rho = \left(\frac{2.63}{2.326}\right)^{1/2} = 1.062$$

I-12

NAS 8-27739

TEST CONFIGURATION

ASSEMBLY
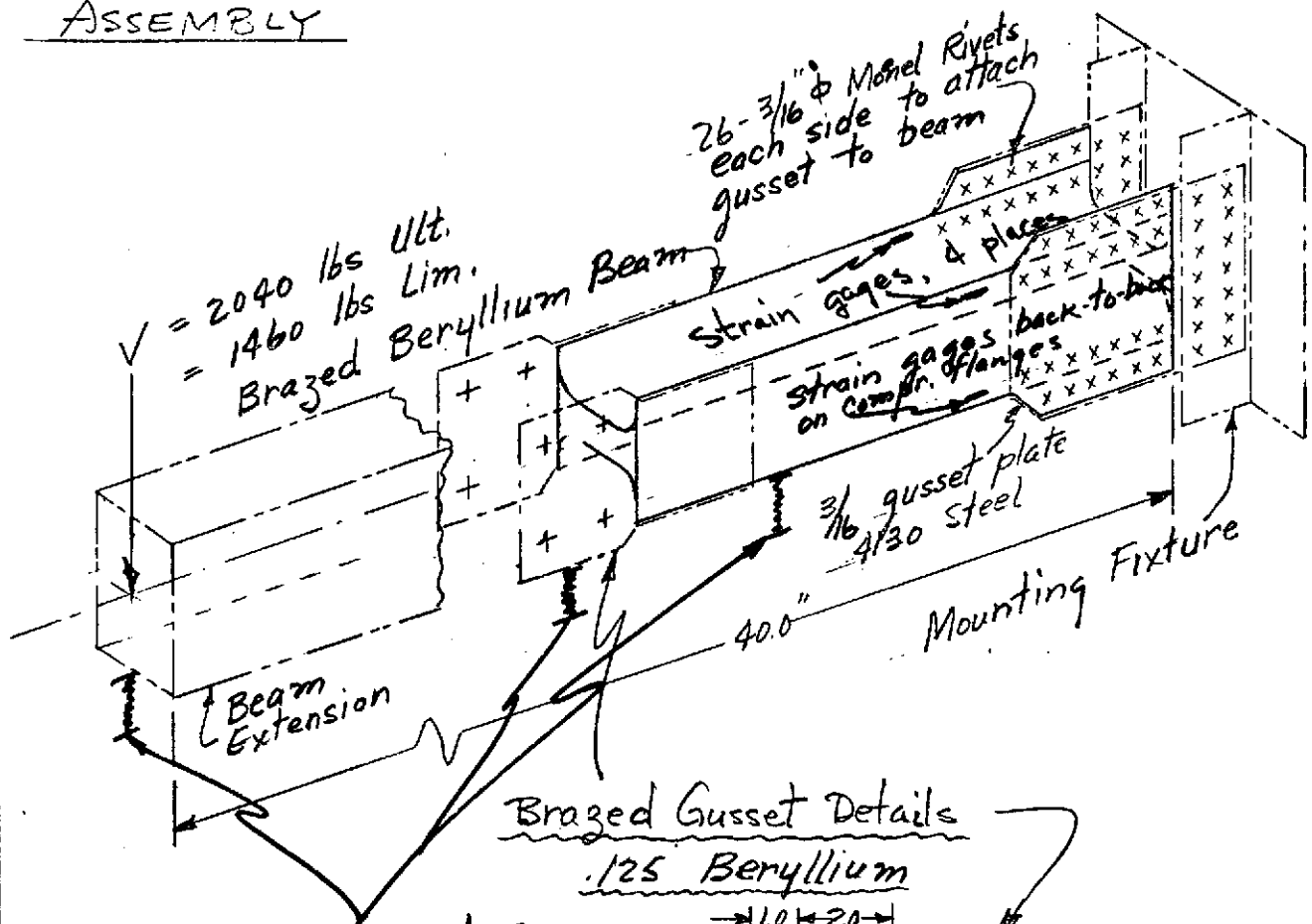
V = 2040 lbs Ult.
   = 1460 lbs Lim.

Brazed Beryllium Beam

26-$\frac{3}{16}$"ϕ Monel Rivets each side to attach gusset to beam

Strain gages, 4 places

Strain gages back-to-back on compr. flanges

$\frac{3}{16}$ gusset plate 4130 steel

Mounting Fixture

40.0"

Beam Extension

3 Deflectometers to monitor hinge action at brazed gusset.

Brazed Gusset Details
.125 Beryllium

1.0   2.0

2.50   1.50

5.00

1.50

0.5   4.0

8.0

2.0   4.0
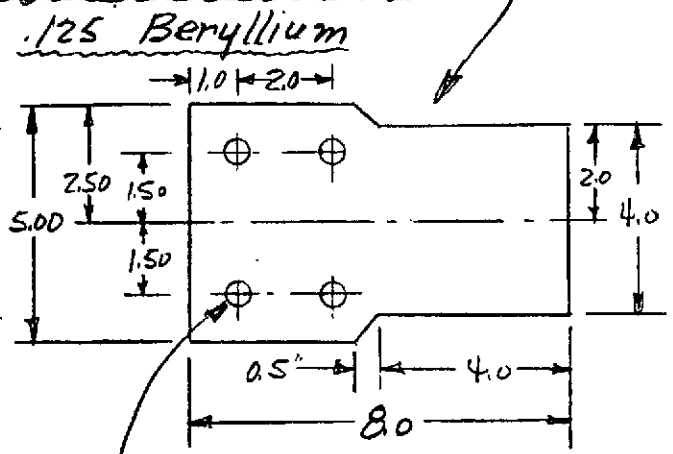
$\frac{1}{2}$"ϕ holes
4 places, each side

FIG. 5

Appendix J

EM B1-M2-7A

STRUCTURAL TEST REQUIREMENTS, UNIFORM LOAD PANEL AND CONCENTRATED LOAD PANEL

ENGINEERING MEMORANDUM

TITLE: STRUCTURAL TEST REQUIREMENTS - UNIFORM LOAD PANEL, SKJ 201002; CONCENTRATED LOAD PANEL, SKC 201001	EM NO: B1-M2-7A, Rev. 6-19-72
	REF:
	DATE: 3- 28-72
AUTHORS: G. S. Fuchigami *GSF*	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Prepare a test requirements document delineating the procedure to be followed in testing two beryllium compression panels at MSFC.

RESULTS

This EM specifies the recommended test setup, the instrumentation requirements, and the test procedure to be used in the compression testing of the uniformly loaded panel, SKJ 201002, and the concentrated load panel, SKC 201001.

DISCUSSION

These test requirements are based on the guidelines provided by the testing of compression subpanels at LMSC.

REVISION A of 6-19-72

Based on the testing conducted at LMSC, a revised time-phased loading diagram is the only significant change recommended to the original requirements of 3-28-72. The revised diagram is shown on Fig. 3B and 6B (pgs. 6B and 11B). The lower rate of loading is recommended to allow more latitude for an abort decision should such appear to be necessary. The success of the LMSC subpanel tests have provided confidence that test objectives and data requirements can be satisfied in the full scale tests. (See EM B1-M5-1)

A. UNIFORM LOAD COMPRESSION PANEL SKJ 201002

This document defines the detail requirements and procedures for the structural
testing to be performed at MSFC on the uniform load panel. The test panel is
shown on SKJ 201002 and the recommended test setup is shown on Fig. 1.

Load Requirements

The following tests should be conducted in the sequence shown:
    1. Room temperature test to 50 percent limit load.
    2. Room temperature test to 100 percent limit load.
    3. Elevated temperature test to 50 percent limit load.
    4. Elevated temperature test to 100 percent limit load.
    5. Elevated temperature test to 140 percent limit load, hold for
        ten seconds, and continue loading to failure.

The test panel and test data must be examined between each test for anomalies
in the recorded data or incipient failures in the test panel.

Two independent methods of reading loads should be used. Continuous recording
of all loads and temperatures during loading periods should be required. Loading
fixtures should be designed or counterbalanced so no additional weight is applied
to the panel and to minimize damage to the panel at failure. Because of the high
energy buildup at ultimate load, adequate safety precautions must be taken to
protect personnel from possible fragmentation of fasteners or material at failure.

Recommended Test Set-Up

The recommended test set-up is shown in Fig. 1. Contractual requirements as well
as design and analyses require that the sides of the panel be simply supported by
the test fixture. The fixture design used for this purpose on the LMSC test sub-
panel is detailed on drawing SKJ 201004, and a similar design is recommended.

INSTRUMENTATION REQUIREMENTS

The panel should be instrumented with strain gages and thermocouples as shown on Fig. 2. Continuous data readout should be required during all loading periods. For purposes of instrumentation calibration no more than 25 percent of any limit loading condition should be applied to the test panel. All instrumentation should be electrically calibrated before each test loading and rechecked at zero load after each test. Dwell periods at limit, ultimate, or other loads should normally not exceed ten seconds to provide for instrumentation stabilization and data readout.

Note: The amount of instrumentation called for in Fig. 2 is considered a maximum. It may be reduced by considerations of symmetry.

TEST PROCEDURE

The load and temperatures should be applied to the test panel per Fig. 3. In the event that premature failure may be imminent (visual, audible, or anomalies in instrumentation readout) the test is to be aborted immediately. Resolution of the problem (if any) must be accomplished before continuing. Adequate safety precautions must be emphasized at all times.

An alternate loading diagram is shown on Fig. 3A, which requires simultaneous load and temperature application. The equipment for this type of loading must be capable of rapidly compensating for the strains due to temperature with respect to the strains due to the direct load, and vice versa. This loading is a better approximation of the mission profile than the loading sequence shown on Fig. 3.

LIAISON, PHOTOS, REPORTS

All test setups shall be reviewed by the test director and/or the structures engineer prior to testing. These same person(s) should be present during the testing. LMSC personnel will be available for participation in all test phases.

Photographic documentation should be provided as follows:
    a. Still (color) photographs of the test setup and test specimen.
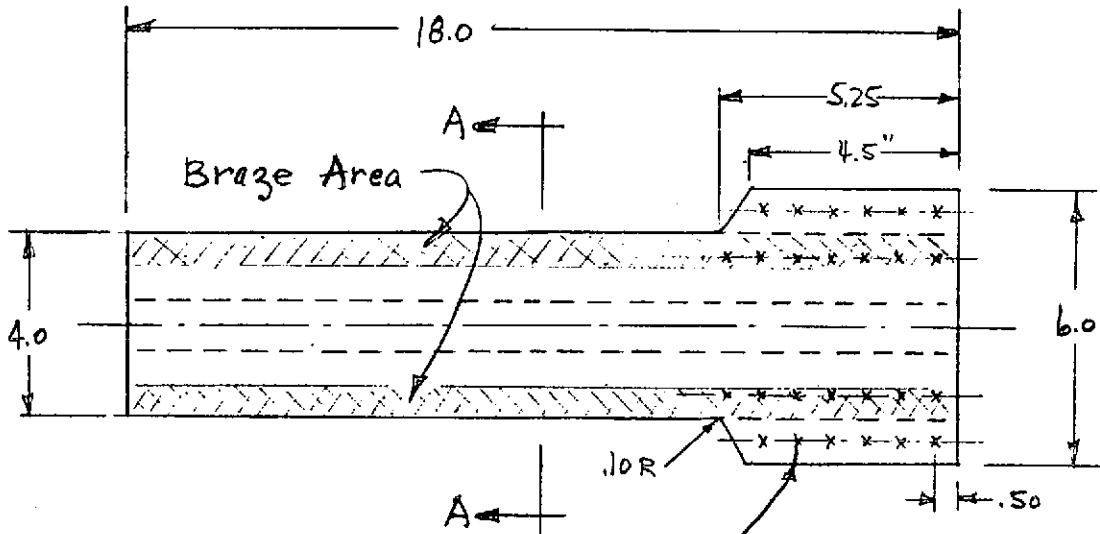   b. Still (color) photographs of the test specimen after the test.

A test report, documenting the entire testing should be submitted to the NAS 8-27739 Program COR, Mr. Geo. Gerry, within 20 days after completion of the tests.

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STRUCTURAL TEST — UNIFORM LOAD PANEL, SKJ 201012

$$P_{Limit} = 5140 \; ^{lb}/_{in}$$

$$= 147,000 \; lbs$$

$$P_{Ultimate} = 7200 \; ^{lbs}/_{in}$$

$$= 209,000 \; lbs$$

TEST TEMPERATURES:
- Room Temp.
- 600° F.

Side Fittings
Similar to SKJ 201004

Personnel Safety Shield
(All Around)

Notes:

1. End fixtures must be capable of uniform loading on test panel.

2. Side fixtures must be maintained in plane throughout testing.

FIG. 1. TEST SET-UP

STRUCTURAL TEST - UNIFORM LOAD PANEL - SKJ 201002

INSTRUMENTATION - FIG 2

Notes:
1. Do not exceed 650°F in adhesive curing operation for strain gages.
2. Temperatures must be uniformly applied — temperature differentials throughout panel must be kept to a minimum.

SECT. C-C

Strain gages back-to-back

Strain Gages on Flanges

Strain gages on flanges.

Strain Gages Back-to-Back

Thermocouples (Adjacent to alternate Gages on Back Side Only)

Strain Gages Back-to-Back

SECT. A-A

SECT. B-B

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STRUCTURAL TEST - UNIFORM LOAD PANEL - SKJ 201002

FIG. 3 - TIME PHASED LOADING

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STRUCTURAL TEST - UNIFORM LOAD PANEL - SKJ 201002

ALTERNATE LOADING DIAGRAM - FIG 3A

FIG 3A. TIME PHASED LOADING (ALTERNATE LOADING DIAGRAM)

NAS 8-27739   EM B1-M2-7A

Based on tests conducted at LMSC of subscale beryllium panels for this contract, the following time-phased loading is recommended for the full size beryllium panel tests at MSFC.

FIG. 3B & 6B

RECOMMENDED TIME PHASED LOADING.

p. 6B & 11B

B.   Concentrated Load Compressions Panel SKC 201001

This document defines the detail requirements and procedures for the structural
testing to be performed at MSFC on the concentrated load panel. The test panel
is shown on SKC 201001 and the recommended test setup is shown on Fig. 4.

Load Requirements

The following tests should be conducted in the sequence shown:
1.   Room temperature test to 50 percent limit load.
2.   Room temperature test to 100 percent limit load.
3.   Elevated temperature test to 50 percent limit load.
4.   Elevated temperature test to 100 percent limit load.
5.   Elevated temperature test to 140 percent limit load, hold for
      ten seconds, continue loading to failure.

The test panel and test data must be examined between each test for anomalies
in the recorded data or incipient failures in the test panel.

Two independent methods of reading loads should be used. Continuous recording
of all loads and temperatures during loading periods should be required. Loading
fixtures should be designed or counterbalanced so no additional weight is applied
to the panel and to minimize damage to the panel at failure. Because of the
stiffness of the beryllium material, adequate safety precautions must be taken
to protect personnel from possible fragmentation at failure.

Recommended Test Set-Up

The recommended test set-up is shown in Fig. 4. Contractual requirements as well
as design and analyses require that the sides of the panel be simply supported
by the test fixture. The fixture design used for this purpose on the LMSC test
sub-panel is detailed on drawing SKJ 201007, and a similar design is recommended.

INSTRUMENTATION REQUIREMENTS

The panel should be instrumented with strain gages and thermocouples as shown
on Fig. 5. Continuous data readout should be required during all loading periods.
For purposes of instrumentation calibration no more than 25 percent of any limit
loading conditions should be applied to the test panel. All instrumentation should
be electrically calibrated before each test loading and rechecked at zero load after
each test. Dwell periods at limit, ultimate, or other loads should normally not
exceed ten seconds to provide for instrumentation stabilization and data readout.

Note: The amount of instrumentation called for in Fig. 5 is considered a maximum.
It may be reduced by considerations of symmetry.

TEST PROCEDURE

The load and temperatures should be applied to the test panel per Fig. 6. In the
event that premature failure may be imminent (visual, audible, or anomalies in
instrumentation readout) the test is to be aborted immediately. Resolution of the
problem (if any) must be accomplished before continuing. Adequate safety pre-
cautions must be emphasized at all times.

An alternate loading diagram is shown on Fig. 6A, which requires simultaneous load
and temperature application. The equipment for this type of loading must be ca-
pable of rapidly compensating for the strains due to temperature with respect to
the strains due to the direct load, and vice versa. This loading is a better
approximation of the mission profile than the loading sequence shown on Fig. 6.

LIAISON, PHOTOS, REPORTS

All test setups should be reviewed by the test director and/or the structures
engineer prior to testing. These same person(s) should be present during the
testing.

Photographic documentation should be provided as follows:
    a. Still (color) photographs of the test setup and test specimen.
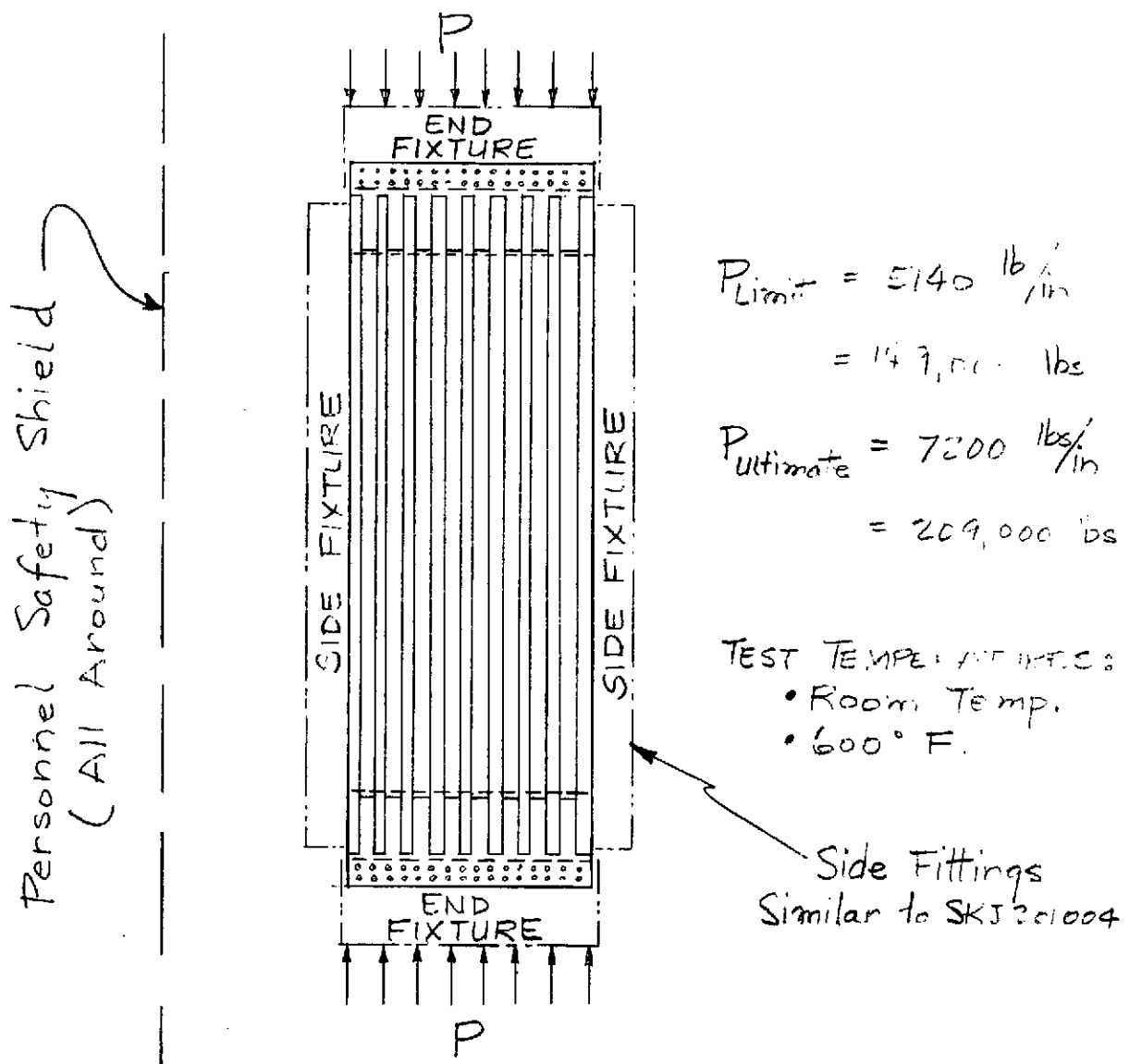   b. Still (color) photographs of the test specimen after the test.

A test report, documenting the entire testing should be submitted to the NAS
8-27739 Program COR, Mr. Geo. Gerry, within 20 days after completion of the tests.

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STRUCTURAL TEST

CONCENTRATED LOAD PANEL - SKC 201001

FIG. 4 - TEST SET-UP

P_{Limit} = 250,000 lbs

$P_{Ultimate}$ = 350,000 lbs

Test Temperatures:
- Room Temp.
- 600° F.

Side Fittings
(Similar to SKJ 201007)

Notes:

1. Load P must be applied over the complete end surface of the concentrated load fitting.

2. End fixture must be capable of uniform loading on test panel.

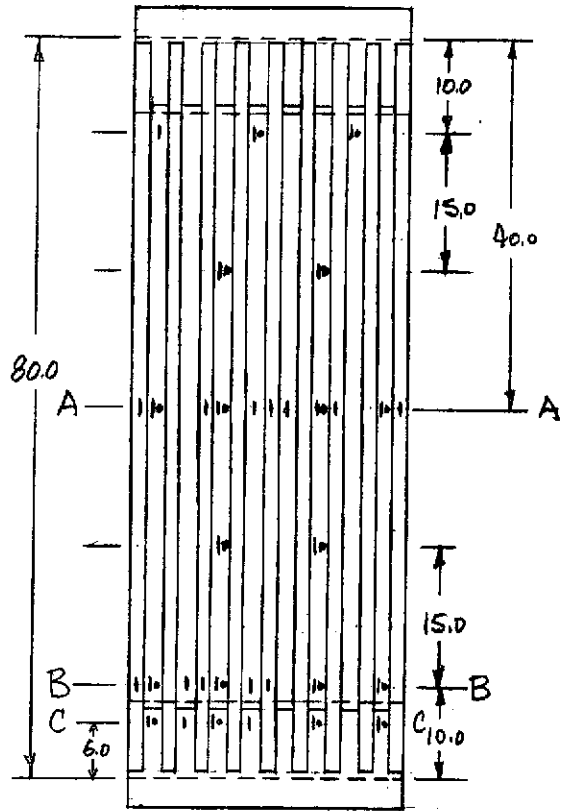3. Side fixtures must be maintained in-plane throughout testing.

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STRUCTURAL TEST - CONCENTRATED LOAD PANEL

SKC-201001

INSTRUMENTATION - FIG. 5

Thermocouples to monitor temperature of beryllium under titanium fitting.
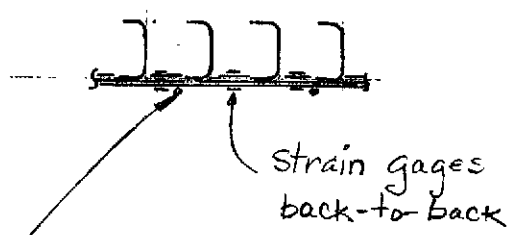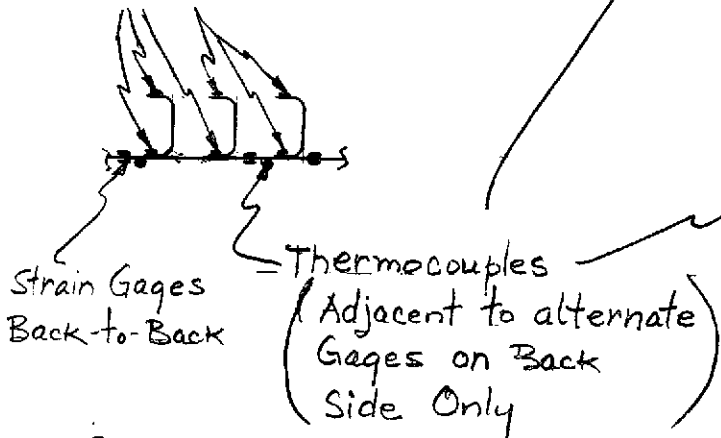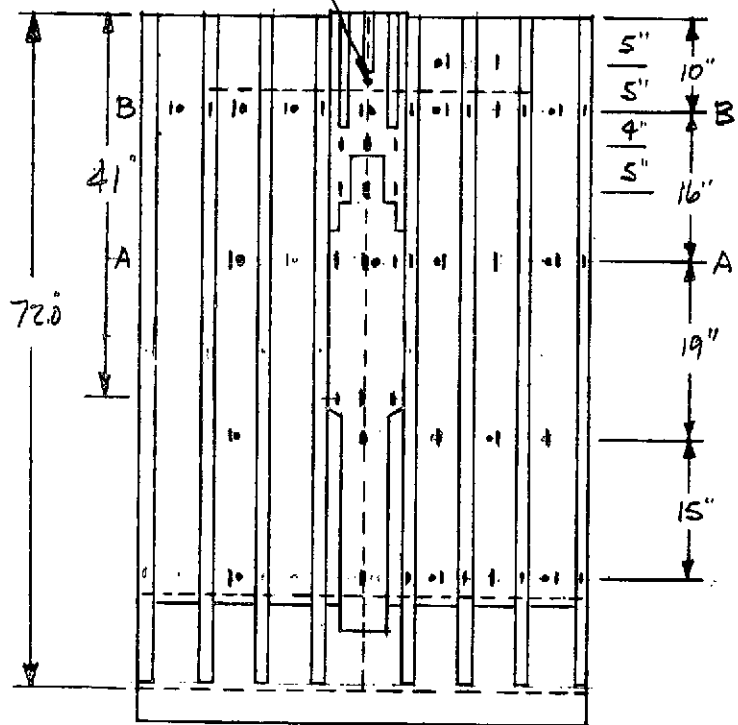
Notes:
1. Do not exceed 650°F. in adhesive curing operations.

2. Temperatures must be uniformly applied — temperature differentials throughout panel must be kept to a minimum.

Strain Gages on Flanges
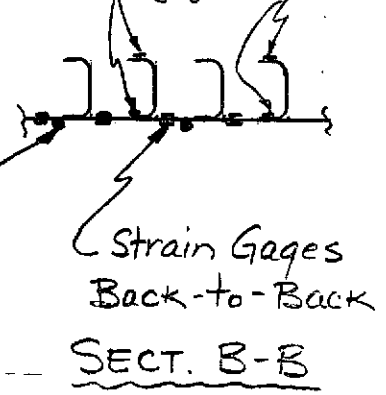
Strain Gages on Flanges

Strain Gages Back-to-Back

Thermocouples (Adjacent to alternate gages) On Back Side Only

SECT. B-B

SECT. A-A

FORM LMSC 362 B-2

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STRUCTURAL TEST – CONCENTRATED LOAD PANEL –SKC 201001

FIG. 6. – TIME PHASED LOADING

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STRUCTURAL TEST - CONCENTRATED LOAD PANEL - SKC201001

ALTERNATE LOADING DIAGRAM - FIG. 6A

FIG. 6A   TIME PHASED LOADING
(ALTERNATE LOADING DIAGRAM)

FORM LMSC 362 B-2

NAS 8-27739   EM B1-M2-7A

Based on tests conducted at LMSC of subscale beryllium panels for this contract, the following time-phased loading is recommended for the full size beryllium panel tests at MSFC.

FIG. 3B & 6B

RECOMMENDED TIME PHASED LOADING.

p. 6B & 11B

Appendix K

EM B1-M2-8

STRESS ANALYSIS OF BERYLLIUM
TRUSS BEAM SKR 201017

ENGINEERING MEMORANDUM

TITLE: STRESS ANALYSES OF BERYLLIUM TRUSS BEAM SKR-201017	EM NO: B1-M2-8 REF: DATE: 3-9-72
AUTHORS: G. S. Fuchigami	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Conduct a stress analysis of the detailed design of a thrust structure truss beam.

RESULTS

This EM documents the stress analyses conducted of Drawing SKR-201017, "Beryllium Truss Beam Assy".

DISCUSSION

Providing the design and analyses of a beryllium thrust structure truss beam is a requirement of NASA contract NAS 8-27739. This EM together with drawing SKR-201017 fulfills this requirement.

NAS 5-27139

THRUST STRUCTURE TRUSS BEAM

GEOMETRY AND LOADING

Ultimate Loads:

$P_{V_1} = 906$ kips

$P_{V_2} = 330$ "

$P_{H_1} = 55$ "

$P_{H_2} = 110$ "

$P_{H_3} = 0$

$R_3 = \dfrac{906}{2} = 453$ kips

Ref LMSC A993110
(Cont. act)

Des. Temp = 200°F

Loads P_{H_1} & P_{H_2} applied 18 below centerline of lower chord members.

Factors of Safety:
1.1 yield
1.4 ultimate

K-2

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

LOAD CALCULATIONS

$\Sigma M_C = 0 \quad +)$

$330(290) + 906(170) + 330(50) - 453(170) - R_1(340)$

$\qquad -0(138) - 55(138) - 110(138) = 0$

$R_1 = \dfrac{330(\overset{340}{290+50}) + 906(170) - 453(170) - 138(55\overset{165}{+110})}{340}$

$\qquad = \underline{\underline{489.5}} \text{ Kips } \text{Ult.} \checkmark$

$\Sigma M_A = 0$

$453(170) + R_2(340) - 330(50) - 906(170) - 330(290)$

$\qquad -0(138) - 55(138) - 110(138) = 0$

$R_2 = \dfrac{330(\overset{340}{50+290}) + 906(170) + 138(55\overset{165}{+110}) - 453(170)}{340}$

$\qquad = \underline{\underline{623.5}} \text{ Kips } \text{Ult.}$

Check: $623.5 + 489.5 + 453 = 330 + 906 + 330$

$\qquad\qquad\qquad 1566 = 1566 \checkmark \qquad ok$

$\Sigma F_H = 0$

$\qquad R_4 = 55 + 110 = \underline{\underline{165}} \text{ Kips } \text{Ult}$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

LOAD CALCULATIONS (Cont'd)

LOAD & REACTION
IN KIPS
LENGTH IN INCHES

$$NAS \, 8 - 27739$$

THRUST STRUCTURE TRUSS BEAM (Cont'd)

LOAD CALCULATIONS (Cont'd)

At A,

489.5 KIPS

$$AD = \frac{130}{120}(489.5) = 530 \text{ KIPS COMPR.}$$

$$AB = \frac{50}{120}(489.5) = 204 \text{ KIPS TENSION}$$

At D
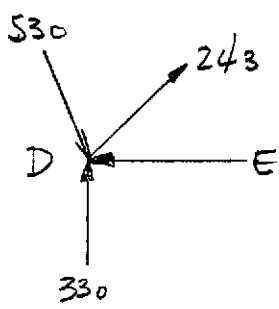
$$\frac{50}{130}(530) + \frac{120}{169.7}(243) - DE = 0$$

$$DE = 204 + 172 = 376 \text{ KIPS COMPRESSION}$$

$$NAS \; 8-27739$$

THRUST STRUCTURE TRUSS BEAM (Cont'd)

LOAD CALCULATIONS (Cont'd)

At C:

$$CF = \frac{130}{120}(623.5) = 675 \; \text{KIPS COMPR.} \checkmark$$

$$\frac{50}{120}(623.5) - 165 - BC = 0$$

$$BC = 260 - 165 = 95 \; \text{KIPS} \checkmark \atop \text{TENSION}$$

At B
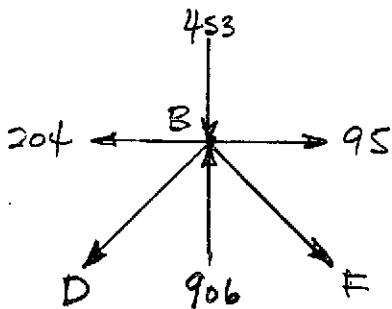
$$\frac{120}{169.7} BF + 95 - 204 - \frac{120}{169.7} BD = 0$$

$$\frac{120}{169.7} BF + 453 - 906 + \frac{120}{169.7} BD = 0$$

$$\frac{240}{169.7} BF + 548 - 1110 = 0$$

$$BF = \frac{562(169.7)}{240} = 398 \; \text{KIPS} \atop \text{TENSION}$$

$$-358 + 702 - \frac{240}{169.7} BD = 0$$

$$BD = \frac{344(169.7)}{240} = 243 \; \text{KIPS} \atop \text{TENSION}$$

THRUST STRUCTURE TRUSS BEAM (Cont'd)

LOAD CALCULATIONS (Cont'd)

AT F:

$$EF - \frac{120}{169.7}(398) - \frac{50}{130}(675) + 110 = 0$$

$$EF = 281 + 260 - 110 = \underline{431} \text{ KIPS}$$

COMPRESSION

$$HF = \frac{120}{130}(675) - \frac{120}{169.7}(398)$$

$$= 622.5 - 281 = \underline{342} \text{ KIPS}$$

COMPRESSION

MOMENT AT F due to P_{H_3} = 110 KIPS

$$= 110 (18) = 1980 \text{ IN-KIPS}$$

MOMENT AT E due to P_{H_1} = 55 KIPS

$$= 55 \times (18") = 990 \text{ IN-KIPS}$$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

LOAD CALCULATIONS (Cont'd)

Truss diagram with nodes A, B, C (top) and D, E, F (bottom). Member loads:
A–B: +204, 170"; B–C: +95, 170"; A–D: −530, 130"; B–D: +243, 169.7"; B–E: −906, 120"; B–F: +398, 169.7"; C–F: −675, 130"; D–E: −376, 120"; E–F: −431, 120". $M_E = 990$ in-kips; $M_F = 1980$ in-kips

ALL LOADING IN KIPS

$(-) =$ Compression
$(+) =$ Tension

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER BE

$4\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{2}$ L, 4 places

$A = 3.25$ in^2 each
$y' = 8'' - 1.0 - 1.14 = 5.86$ in
$x' = 4.0 - 1.0 - .14 = 2.86$ in
$I_{o_x} = 6.57$ in^4 $I_{o_y} = 1.46$ in^4
$t_1 = t_2 = 0.5''$

Total Area:
$A_{Tot} = \frac{1}{2}(32.0 + 14.0) + 4(3.25)$

$= 23.0 + 13.0 = 36.0$ in^2

$$I_{xx} = 2\left[0.5\frac{(16.0^3)}{12}\right] + 2\left[3.5(7.75^2)\right] + 4\left[3.25(5.86)\right] + 4(6.57)$$

$$= 341.0 + 420.0 + 446 + 26.3 = 1233 \text{ in}^4$$

$$I/c = \frac{1233}{8.0} = 154.0 \text{ in}^3$$

$$I_{yy} = 2\left[0.5\frac{(7.0^3)}{12}\right] + 2\left[8.0(3.75^2)\right] + 4\left[3.25(2.86^2)\right] + 4(1.46^2)$$

$$= 28.6 + 225 + 106.0 + 8.5 = 368.1 \text{ in}^4$$

ITEM	COLUMN NO.	1	2	3	4	5	6	7	8	9	10	11
	DESCRIPTION	a	y	ay	ay^2	I_{ox}	x	ax	ax^2	I_{cy}	$a xy$	
	OPERATION			①②	②③			①④	⑦④		⑥⑨	
1	2.50 × 0.50	1.250	0.25	.312	.078	.026	1.25	1.562	1.955	.650		
2	4.00 × 0.50	2.000	2.50	5.00	12.500	2.667	0.25	0.500	.125	.041		
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
Σ		3.250		5.312	12.578	2.693		2.062	2.080	.691		

$$\bar{y} = ⑫ = \frac{\Sigma ay}{\Sigma a} = \frac{③}{①} = 1.635 \text{ in.}$$

$$I_x = ⑬ = -\bar{y}\Sigma ay + \Sigma ay^2 + \Sigma I_{ox}$$
$$= -⑫③ + ④ + ⑤$$
$$= 6.57 \text{ in.}^4$$

$$P_x = \sqrt{\frac{I_x}{\Sigma a}} = \frac{⑬}{①} = \underline{\quad} \text{ in.}$$

$$\bar{x} = ⑭ = \frac{\Sigma ax}{\Sigma a} = \frac{⑦}{①} = .635 \text{ in.}$$

$$I_y = ⑮ = -\bar{x}\Sigma ax + \Sigma ax^2 + \Sigma I_{cy}$$
$$= -⑭⑦ + ⑧ + ⑨$$
$$= 1.46 \text{ in.}^4$$

$$P_y = \sqrt{\frac{I_y}{\Sigma a}} = \frac{⑮}{①} = \underline{\quad} \text{ in.}$$

$$I_{xy} = -\bar{y}\bar{x}\Sigma a + \Sigma axy + \Sigma I_{oxy} = -①③ + ⑩ + ⑪ = \underline{\quad} \text{ in.}^4$$

1. NOTE SIGN OF I_{xy} MAY BE POSITIVE OR NEGATIVE.

2. I_{oxy} IS PRODUCT OF INERTIA OF ITEM ABOUT CENTROIDAL AXES PARALLEL TO ARBITRARY AXES.
   I_{oxy} = 0 IF ITEM IS SYMMETRICAL ABOUT EITHER AXIS.

3. × HORIZONTAL (+) TO RIGHT, FROM ARBITRARY y AXIS.
   y VERTICAL (+) UP, FROM ARBITRARY × AXIS.

Column Buckling Curve
Beryllium Cross-Rolled Plate

This Curve extrapolated from EMBI-M2-1

for Fcy = 45 KSI   BSF 2-10-72

Allowables at 200°F are
estimated at 95% R.T. values

Beryllium Truss Beam

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EM Bulletin

NAS 8-27739

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R.T.
200°F

Fcc (10³ psi)

50
40
30
20
10

0   20   40   60   80   100   120   140   160

ℓ'/ρ

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER BE (Cont'd)

$$\rho = \left(\frac{368.1}{36.0}\right)^{1/2} = (10.2)^{1/2} = 3.19$$

$$L'/\rho = 120/3.19 = 37.6$$

$$F_{co_{200°F}} = 40\ KSI \qquad Ref\ p.\ A-2$$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER BE (Cont'd)

Moment at E will be resisted by BE, DE, and EF. The magnitude of the moment reacted by each member will be proportional to their stiffnesses. Based on previous calculations, M_E will be distributed as follows:

$$\left(\begin{array}{ll} \text{For } I_{BE} = 163.9 & \text{These are from prelim. Calcs.} \\ I_{DE} = 19.2 & \text{Stiffness factor } EI/L \propto \text{to } I \\ I_{EF} = \dfrac{30.6}{213.7} & \text{when } E \text{ \& } L \text{ are constant.} \end{array}\right)$$

$$M_{BE} = \frac{163.9}{213.7} \times 990 = 760 \text{ in-kips}$$

$$M_{DE} = \frac{19.2}{213.7} \times 990 = 89 \quad \text{'' ''}$$

$$M_{EF} = \frac{30.6}{213.7} \times 990 = 141 \quad \text{'' ''}$$

After final sizing, this distribution will be re-checked.

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

Similarly, the moment at F will be initially distributed; however, as the lengths of the members differ, the moment will be distributed with respect to their stiffness factors $K = \frac{I}{L}$

$$\text{For } I_{CF} = 64.5 \qquad K = \frac{64.5}{130} = .496$$

$$I_{EF} = 30.6 \qquad K = \frac{30.6}{120} = .257$$

$$I_{BF} = 3.8 \qquad K = \frac{3.8}{164.7} = \underline{.0022}$$

$$.755$$

$$M_{CF} = \frac{.496}{.755} \times 1980 = 1300 \text{ in-kips}$$

$$M_{EF} = \frac{.257}{.755} \times 1980 = 674 \text{ in-kips}$$

$$M_{BF} = \frac{.0022}{.755} \times 1980 = 6 \text{ in-kips}$$

$$\underline{NAS\ 8-27739}$$

$$\underline{THRUST\ STRUCTURE\ TRUSS\ BEAM\ (Cont'd)}$$

$$\underline{MEMBER\ BE\ (Cont'd)}$$

$$\hat{f}_{co} = \frac{906}{36.0} = 25.2\ KSI$$

$$M' = \frac{760}{1-\frac{25.2}{40}} = \frac{760}{.370} = 2055\ in\text{-}kips$$

$$f_{bc_o} = \frac{2055}{154.0} = 13.4\ KSI$$

$$f_{co} + f_{bc_o} = 25.2 + 13.4 = 38.6\ KSI$$

FORM LMSC 362 B-2

THRUST STRUCTURE TRUSS BEAM (Cont'd)   NAS8-27739

MEMBER CF

Try same section as member BE

$$L'/_\rho = 130/_{3.19} = 40.7$$

$$F_{co} \cong 40 \text{ KSI} \qquad \text{Ref. p. A-2}$$

$$f_{co} = \frac{675}{36.0} = 18.8 \text{ KSI}$$

$$M' = \frac{1300}{1 - \frac{18.8}{40}} = \frac{1300}{.53} = 2450 \text{ in. kips}$$

$$f_{bco} = \frac{2450}{154} = 15.9 \text{ KSI}$$

$$f_{co} + f_{bco} = 18.8 + 15.9 = 34.7 \text{ KSI}$$

FORM LMSC 362 B-2

NAS 8-27739

Thrust Structure Truss Beam

Member EF
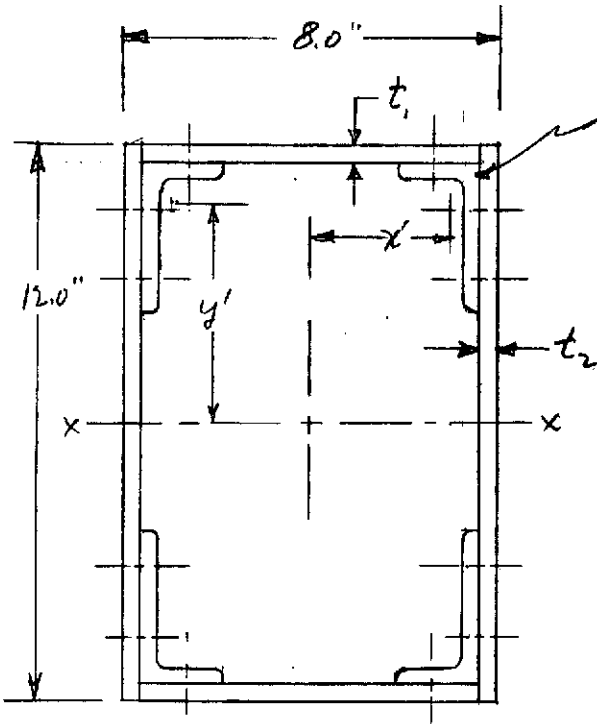
$3\frac{1}{4} \times 1\frac{3}{4} \times \frac{3}{8} L$ 4 places

Area = 1.73 in²

$y' = 6.0 - \frac{3}{8} - 1.2 = 4.425''$

$x' = 4.0 - \frac{3}{8} - .45 = 3.175''$

$I_{o_x} = 1.83 \text{ in}^4 \quad I_{o_y} = .41 \text{ in}^4$

$t_1 = t_2 = \frac{3}{8}''$

Total Area:

$A_{Tot} = \frac{3}{8}(24.0 + 14.5) + 4(1.73)$

$= 14.4 + 6.9 = 21.3 \text{ in}^2$

$I_{xx} = 2\left[.375\frac{(12.0^3)}{(12)}\right] + 2\left[2.72(5.8^2)\right] + 4(1.83) + 4\left[1.73(4.425)^2\right]$

$= 108 + 183.5 + 7.3 + 135.5 = 434.3 \text{ in}^4$

$\frac{I}{c} = \frac{434.3}{6.0} = 72.2 \text{ in}^3$

$I_{yy} = 2\left[.375\left(\frac{7.25^3}{12}\right)\right] + 2\left[4.5(3.8^2)\right] + 4(0.41) + 4\left[1.73(3.175)^2\right]$

$= 23.8 + 129 + 1.6 + 69.2 = 223.6 \text{ in}^4$

$\rho = \left(\frac{223.6}{21.3}\right)^{1/2} = (10.5)^{1/2} = 3.24 \text{ in}$

SECTION PROPERTIES

COLUMN NO.	1	2	3	4	5	6	7	8	9	10	11
DESCRIPTION	a	y	ay	ay^2	I_{ox}	x	ax	$a?$	acy	axy	
OPERATION			①②	②③			①④	③④		②③	
1 1.75 x .375	.655	.1875	.1230	.0230	.0076	.875	.572	.500	.209		
2 2.875 x .375	1.077	1.812	1.950	3.540	.741	.1875	.202	.038	.0126		
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
Σ	1.732		2.073	3.563	.740		.774	.538	.221		

$$\bar{y} = ⑫ = \frac{\Sigma ay}{\Sigma a} = \frac{③}{①} = 1.195 \text{ in.}$$

$$I_x = ⑬ = -\bar{y}\Sigma ay + \Sigma ay^2 + \Sigma I_{ox}$$
$$= -⑫③ + ④ + ⑤$$
$$= 1.831 \text{ in.}^4$$

$$P_x = \sqrt{\frac{I_x}{\Sigma a}} = \frac{⑬}{①} = \underline{\hspace{1cm}} \text{ in.}$$

$$\bar{x} = ⑭ = \frac{\Sigma ax}{\Sigma a} = \frac{⑦}{①} = .446 \text{ in.}$$

$$I_y = ⑮ = -\bar{x}\Sigma ax + \Sigma ax^2 + \Sigma I_{oy}$$
$$= -⑭⑦ + ⑧ + ⑨$$
$$= .413 \text{ in.}^4$$

$$P_y = \sqrt{\frac{I_y}{\Sigma a}} = \frac{⑮}{①} = \underline{\hspace{1cm}} \text{ in.}$$

$$I_{xy} = -\bar{y}\bar{x}\Sigma a + \Sigma axy + \Sigma I_{oxy} = -⑫③ + ⑩ + ⑪ = \underline{\hspace{1cm}} \text{ in.}^4$$

1. NOTE SIGN OF I_{xy} MAY BE POSITIVE OR NEGATIVE.

2. I_{oxy} IS PRODUCT OF INERTIA OF ITEM ABOUT CENTROIDAL AXES PARALLEL TO ARBITRARY AXES.
   I_{oxy} = O IF ITEM IS SYMMETRICAL ABOUT EITHER AXIS.

3. x HORIZONTAL (+) TO RIGHT, FROM ARBITRARY y AXIS.
   y VERTICAL (+) UP, FROM ARBITRARY x AXIS.

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER EF (Cont'd)

$$L = 120'' \qquad L' \cong \frac{120}{2} = 60$$

$$\frac{L'}{\rho} = \frac{60}{3.24} = 18.5 \qquad F_{co} = 42.0 \quad \text{Ref } p. A-2$$

$$f_{co} = \frac{431}{21.3} = 20.2 \, KSI$$

$$M' = \frac{674}{1 - \frac{20.2}{42.0}} - \frac{674}{.518} = 1300 \, \text{in. Kips}$$

$$f_{b_{co}} = \frac{1300}{72.2} = 18.0 \, KSI$$

$$f_{co}' + f_{b_{co}} = 20.2 + 18.0 = 38.2 \, KSI$$

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$$\underline{NAS8 \cdot 27739}$$

THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER DE

$2 \times 2 \times 5/16 \, \angle$, 4 places

$A = 1.15 \ in^2 \ each$

$y' = x' = 4.0 - .312 - .61 = 3.08''$

$I_{0_x} = I_{0_y} = 0.42 \ in^4$

$t_1 = t_2 = 5/16''$

$A_{Tot} = 9.6 + 4(1.15) = 14.2 \ in^2$

$$I_{xx} = 2\left[.312 \frac{(8.0^3)}{12}\right] + 2\left[2.3(3.84^2)\right] + 4(.42) + 4\left[1.15(3.08^2)\right]$$

$$= 26.5 + 67.8 + 1.7 + 43.7 = 139.7 \ in^4$$

$$I/c = \frac{139.7}{4.0} = 34.9 \ in^3$$

$$I_{yy} = I_{xx} = 139.7 \ in^4$$

$$\rho = \left(\frac{139.7}{14.2}\right)^{1/2} = (9.84)^{1/2} = 3.14 \ in$$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER DE (Cont'd)

$$L'/\rho = 120/3.14 = 38.2$$

$$F_{co} = 40.0 \ KSI \qquad Ref. \ p. \ A-2$$

$$f_{co} = 376/14.2 = 26.5 \ KSI$$

$$M' = \frac{89}{1 - \frac{26.5}{40.0}} = \frac{89}{.337} = 264 \ in \cdot Kips$$

$$f_{b_{co}} = 264/34.9 = 7.57 \ KSI$$

$$f_{cc} + f_{b_{co}} = 26.5 + 7.57 = 34.1 \ KSI$$

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<u>NAS8-27739</u>

<u>THRUST STRUCTURE TRUSS BEAM (Cont'd</u>

<u>MEMBER AD</u>

Try $8.0 \times 8.0 \times 5/16''$ Section with

$2 \times 2 \times 5/16$ Ls in 4 corners. $\left(\substack{\text{Same as} \\ \text{member DE}}\right)$

$A_{Tot} = 14.2 \ in^2$

$I_{xx} = I_{yy} = 139.7 \ in^4$ } Ref p. H

$\rho = 3.14 \ in$

$L'/\rho = 130/3.14 = 41.4$

$F_{co} = 39.6 \ KSI \qquad$ Ref. p. A-2

$f_{co} = 530/14.2 = 37.4 \ KSI$

THRUST STRUCTURE TRUSS BEAM (Cont'd)

NAS8-27739

MEMBER BF

$2 \times 2 \times \frac{3}{8} \angle$, 4 Places

$A = 1.36 \text{ in}^2$ each

$I_o = .48 \text{ in}^4$

$y' = 4.0 - \frac{3}{8} - .64 = 2.99 \text{ in}$

$x' = \frac{3}{16} + .64 = .83 \text{ in}$

$A_{Tot} = 2\left(\frac{3}{8}\right)(6.0) + \frac{3}{8}(7.25) + 4(1.36)$

$= 4.5 + 2.7 + 5.4 = 12.6 \text{ in}^2$

Net Area $= A_{Tot} - A_{Holes}$ ($\frac{3}{8}$" holes)

$= 12.6 - 4\left(\frac{3}{8}\right)\left(\frac{3}{4}\right) + 2\left(\frac{3}{8}\right)\left(\frac{9}{8}\right)$

$= 12.6 - 1.12 - .65 = 10.8 \text{ in}^2$

$I_{yy} = 2\left[.375 \frac{(6.0^3)}{12}\right] + 4(.48) + 4\left[1.36(.83^2)\right]$

$= 13.5 + 1.9 + 3.7 = 19.1 \text{ in}^4$

$I/c = \frac{19.1}{3} = 6.37 \text{ in}^3$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)   NAS8-27739

MEMBER BF (Cont'd)

$$f_{tu} = \frac{398}{10.8} = 36.8 \ KSI$$

$$f_{bu} = \frac{6}{6.37} = .94 \ KSI$$

$$f_{tu} + f_{bu} = 36.8 + .9 = 37.7 \ KSI$$

$$F_{tu} = 60 \ KSI \qquad Ref. \ MIL-B-8964$$

$$M.S. = \frac{60}{37.7} - 1 = .59$$

Yield check at limit load;

$$f_{ty} + f_{by} = \frac{37.7}{1.4} = 26.9 \ KSI$$

$$F_{ty} = 40 \ KSI \qquad Ref. \ MIL-B-8964$$

$$M.S._{Yield} = \frac{40}{26.9} - 1 = .49 \qquad \left(\begin{array}{l} .10 \ req'd \ by \ Contr. \\ O.K. \end{array} \right)$$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

REDISTRIBUTION OF MOMENTS AT E AND F, AND RECHECK OF BEAM SIZES

Moment at E:

$$\text{For } I_{BE} = 1233 \text{ in}^4$$
$$I_{DE} = 139.7 \text{ "}$$
$$I_{EF} = \underline{434 \text{ "}}$$
$$1806.7$$

(Calculated I_b)

$$M_{BE} = \frac{1233}{1807} \times 990 = 677 \quad \text{in-kips}$$

$$M_{DE} = \frac{139}{1807} \times 990 = 76 \quad \text{"} \quad \text{"}$$

$$M_{EF} = \frac{434}{1807} \times 990 = 238 \quad \text{"} \quad \text{"}$$

Moment at F:

$$\text{For } I_{BF} = 1233 \text{ in}^4 \qquad K = \frac{1233}{130} = 9.50$$
$$I_{EF} = 434 \text{ "} \qquad K = \frac{434}{120} = 3.61$$
$$I_{BF} = \underline{19.1} \qquad K = \frac{19.1}{169.7} = \underline{.11}$$
$$1686.1 \qquad\qquad\qquad 13.22$$

$$M_{CF} = \frac{9.50}{13.22} \times 1980 = 1423 \quad \text{in-kips}$$

$$M_{EF} = \frac{3.61}{13.22} \times 1980 = 540 \quad \text{"} \quad \text{"}$$

$$M_{BF} = \frac{.11}{13.22} \times 1980 = 17 \quad \text{"} \quad \text{"}$$

THRUST STRUCTURE TRUSS BEAM (Cont'd) $\overline{NAS\ 8-27739}$

MOMENT RE-DISTRIBUTION AND RECHECK (Cont'd)

MEMBER	REVISED MOMENTS IN-KIPS M	M'	f_{bco}	f_{co}	$f_{co}+f_{bco}$	F_{co}	M.S.
BE	677	1830	11.9	25.2	37.1	40.0	.08
DE	76	225	6.5	26.5	33.0	40.0	.21
EF	238	460	6.4	20.2	26.6	42.0	.58
CF	1423	2690	17.5	18.8	36.3	40.0	.10
EF	540	1040	14.4	20.2	34.6	42.0	.21
BF	17	—	—	—	—	This member is loaded in tension	

SUMMARY OF
MARGINS OF SAFETY (M.S.) OF TENSION MEMBERS

MEMBER	f_{btu}	f_{tu}	$f_{bt}+f_{tu}$	F_{tu}	F_{ty}	M.S.yield	M.S.ult.
BF	.94	36.8	37.7	60	40	.49	.59
BD	—	46.8	46.8			.19	.28
AB	—	39.2	39.2			.43	.53
BC	—	24.4	24.4			1.30	1.46

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

MEMBER BD

2x2x ¼ L, 4 places
A = 0.94 in² each

$$A_{Tot} = \frac{1}{4}(8.0) + 4(0.94) = 5.76 \text{ in}^2$$

$$A_{Tension} = 5.76 - 2(\tfrac{3}{8})(\tfrac{3}{4}) = 5.2 \text{ in}^2$$

$$f_{tu} = \frac{243}{5.2} = 46.8 \text{ KSI} \qquad F_{tu} = 60 \text{ KSI, ok.}$$

Use this section for AB $f_{tu} = 39.2$ KSI

MEMBER BC

1½ × 1½ × ¼ L, 4 places
A = .69 in² each
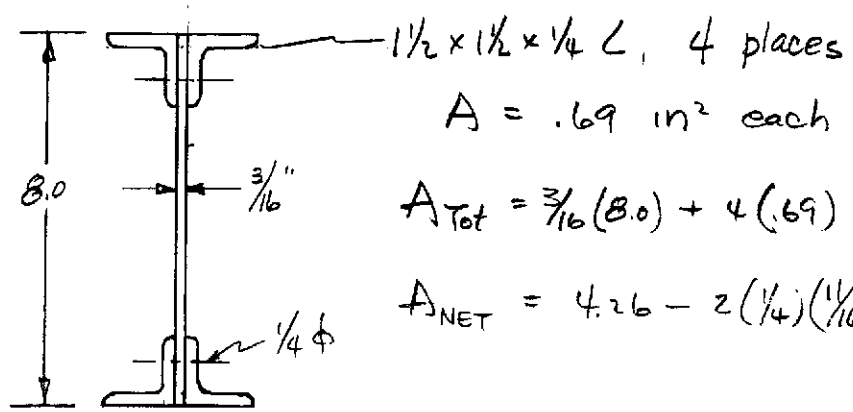
$$A_{Tot} = \tfrac{3}{16}(8.0) + 4(.69) = 4.26 \text{ in}^2$$

$$A_{NET} = 4.26 - 2(\tfrac{1}{4})(\tfrac{11}{16}) = 3.9 \text{ in}^2$$

$$f_{tu} = \frac{95}{3.9} = 24.4 \text{ KSI} \qquad OK.$$

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

BEAM MEMBER FASTENER REQ'MENTS

h = beam height

M' = Applied beam-Column moment.
(Ref p. N)

MEMBER BE   (Ref p. A)

$M'_{applied} = 1830$ in-kips

d = distance betw. centroids.
$= 10.0$ in.

p = equivalent Couple load to $M'_{applied}$

$= \dfrac{1830}{10} = 183$ kips

= Shear in side plates = V

$g = \dfrac{V}{h} = \dfrac{183}{2(16)} = 5.72$ kips/in

This g will be reacted by two rows of attachments in this member.

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

BEAM MEMBER FASTENER REQ'MENTS (Cont'd)

MEMBER BE (Cont'd)

$\frac{1}{2}"\phi$ HI-LOKS will be used as fasteners

$$Mt'l = 6Al-4V \text{ titanium alloy}$$
$$F_{su} = 95 \text{ KSI}$$

$$P_{ult \ shear} = 18,650 \text{ lbs.}$$

$$S_{max} = \frac{18.65(2)}{5.72} = 6.5 \text{ inches spacing}$$

Check for buckling between fasteners.

$$\frac{S}{t} \cong 30 \qquad Ref. \ EM-B1-M2-1$$

$$S \cong \frac{1}{2}(30) = 15 \text{ inches.}$$

THRUST STRUCTURE TRUSS BEAM (Cont'd)

NAS8-27734

BEAM MEMBER FASTENER REQU'MENTS (Cont'd)

MEMBER	M' in-kips	h in.	d in	P KIPS	q Kips/in	Attachment Size	Allow. Shear, Pult (Kips)	Rows of Fasteners	Spacing Smax (in)	S(Fir) Buckling
BE	1830	16.0	10.0	183	5.72	1/2" φ	18.65	2	6.5	15
DE	225	8.0	5.0	45	2.81	5/16" φ	7.3	1	2.6	9.5
EF	1040	12.0	8.0	130	5.42	3/8" φ	10.5	2	3.9	11
CF	2690	16.0	10.0	269	8.4	1/2" φ	18.65	2	4.5	15
BF	17	6.0	1.5	11.3	1.88	3/8" φ	10.5	1	5.6	11
AD	—	8.0	5.0	—	—	5/16" φ	7.3		8.0	9.5
BD	—	4.25		—	—	1/4" φ	4.65		6.0	7.5
BC	—	3.25		—	—	1/4" φ	4.65		6.0	7.5
AB	—	4.25		—	—	1/4" φ	4.65		6.0	7.5

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THRUST STRUCTURE TRUSS BEAM

JOINT DETAILS AT E

3/4" LOCKALLOY PLATE

40 - 1/2" φ Each Side

40 - 3/8" φ Each Side

26 - 3/8" φ Each Side
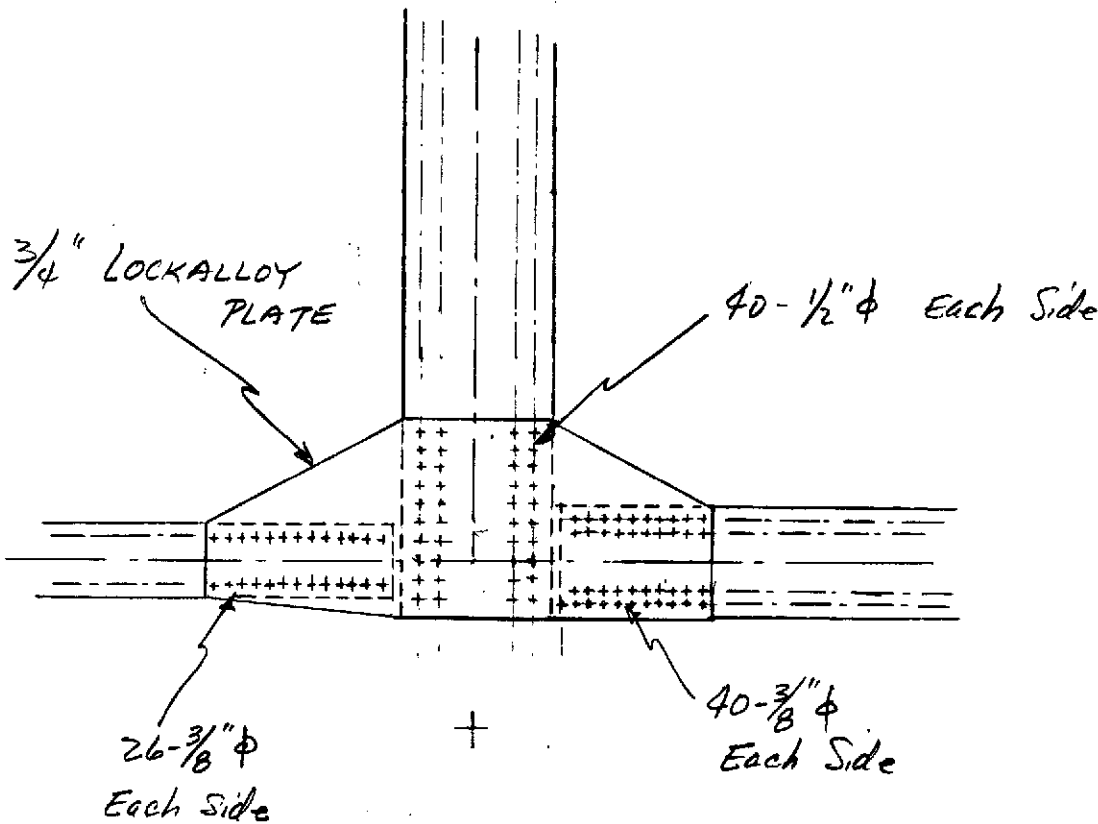
Single Shear Capability of titanium fasteners:

$1/2" \phi = 18.650$ lbs Ult.

$3/8" \phi = 10,500$ " "

$1/4" \phi = 4,650$ " "

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

JOINT DETAILS AT F.

3/4" LOCKALLOY PLATE

16-1/2"ϕ Each Side

48-1/2"ϕ Each Side

45-3/8"ϕ Each Side

10-3/4"ϕ Each Side

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THRUST STRUCTURE TRUSS BEAM (Cont'd)

JOINT DETAILS (Cont'd)

LOCKALLOY GUSSET PLATES

Bearing check at fastener holes.

$$F_{bry} = 65 \text{ KSI}$$
$$F_{bru} = 74 \text{ KSI}$$

Ref. LMSC 679606

FASTENER SIZE in	SINGLE SHEAR ALLOWABLE (Ti Hi-Loks) lbs	LOCKALLOY THICKNESS in	BEARING AREA in²	ALLOWABLE LOADING	
				P_{bry} lbs	P_{bru} lbs
1/4	4650	3/4	.1875	12,200	13,900
5/16	7300		.234	15,200	17,100
3/8	10,500		.281	18,300	20,800
7/16	14,300		.328	21,300	24,200
1/2	18,650		.375	24,400	27,800

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Appendix L

EM B1-M2-9

STRESS ANALYSIS OF BERYLLIUM
SHEAR BEAM SKR 201020

ENGINEERING MEMORANDUM

TITLE:		EM NO: B1-M2-9
STRESS ANALYSES OF BERYLLIUM SHEAR BEAM. SKR 201020		REF:
		DATE: 3-31-72
AUTHORS: G. S. Fuchigami *GSF*		APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Conduct a stress analysis of the detailed design of a thrust structure shear web beam.

RESULTS

This EM documents the stress analyses conducted of Drawing SKR-201020, "Beryllium Shear Web Beam Assembly".

DISCUSSION

Providing the design and analyses of a beryllium thrust structure shear beam is a requirement of NASA Contract NAS 8-27739. This EM together with drawing SKR 201020 fulfills this requirement.

THRUST STRUCTURE SHEAR WEB BEAM

GEOMETRY AND LOADING

NAS8-27739

· Ultimate Loads

(Safety factors:
1.1 yield
1.4 ultimate)

Ref. Contract, fig 4 of Exhibit 'A'

$P_{V_1} = 452$ KIPS

$P_{V_2} = 330$ KIPS

$P_{H_1} = 55$ kips

$P_{H_2} = 110$ kips

$P_{H_3} = 0$

Design Temp. = 200°F.

P_{H_1} & P_{H_2} applied 12 inches below lower surface of lower cap.

Upper and lower beam caps supported laterally at load introduction points

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

REACTION CALCULATIONS

$\Sigma F_H = 0$

$$R_3 = 55 + 110 = \underline{\underline{165}} \text{ KIPS}$$

$\circlearrowleft \Sigma M_{R_1} = 0$

$$360 R_2 = 330(60) + 453(180) + 330(300) + 165(112-100)$$

$$R_2 = \frac{19800 + 81500 + 99000 + 1980}{360} = \frac{202,280}{360}$$

$$= 562 \text{ KIPS} \checkmark$$

$\circlearrowleft \Sigma M_{R_2} = 0$

$$360 R_1 = 330(60) + 453(180) + 330(300) + 165(100-112)$$

$$R_1 = \frac{19800 + 81,500 + 99000 - 1980}{360} = \frac{198320}{360}$$

$$= 551 \text{ KIPS} \checkmark$$

Check:

$\Sigma F_V = 0$

$$562 + 551 = 1113 \text{ KIPS}$$
$$330 + 453 + 330 = 1113 \text{ KIPS}$$

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

WEB SHEAR & CAP LOADS

Shears are in lbs/in

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

SHEAR WEB ANALYSIS

The shear webs will be designed with stiffened panels due to considerations of material procurement and reduced mechanical properties of plate material. Both end bays will be made non-buckling in order to preclude beam-column action in the end frames. The center bays will be analyzed as semi-tension field panels in order to reduce weight.

Preliminary analyses indicate that the following gages and stiffener spacings are optimum:

End Bays — $t = .1875''$, spacing = 10 inches

Middle " — $t = .10''$, " = 12 "

NASE-27739

Thrust Structure Shear Web Beam (Cnt'd)
Shear Web Analysis (Cnt'd)

END BAYS - PANEL

$a = 100''$, $b = 10''$ $\frac{a}{b} = \frac{100}{10} = 10$ $t = .1875''$

$K_s = 5.35$ Ref. NACA TN 3781

$\sqrt{K_s} = \sqrt{5.35} = 2.31$

$\frac{b}{(t\sqrt{K_s})} = \frac{10}{.1875(2.31)} = 23.1$

$F_{s_{cr}} = 31.5$ KSI   Ref. EM B1-M2-1, Fig. 2

$q_{cr} = 31,500(.1875) = 5900$ lbs/in

$q_{applied} = 5620$ lbs/in

Try $t = .180''$, at $a = 100''$, $b = 10''$

$\sqrt{K_s} = 2.31$ $\frac{b}{(t\sqrt{K_s})} = \frac{10}{.180(2.31)} = 24.1$

$F_{s_{cr}} = 31.3$ KSI   Ref EM B1-M2-1, Fig 2

$q_{cr} = 31,300(.180) = 5630$ lbs/in

$M.S. = \frac{5630}{5620} - 1 = 0.0$ OK

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NAS 8-27??

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

SHEAR WEB ANALYSIS (Cont'd)

END BAYS - STIFFENERS

Ref. BRUHN, C10.10

$$\frac{I_v}{d t^3} = \frac{.0217}{\left(\frac{d}{h \sqrt{K_s}}\right)^{8/3}}$$

Where

I_v = Req'd. moment of Inertia of Stiffener

d = ℄ to ℄ spacing of stiffeners

t = Skin or web thickness

h = panel height

K_s = Shear buckling coefficient

$$\frac{d}{h \sqrt{K_s}} = \frac{10}{100 \sqrt{5.35}} = \frac{10}{100 (2.31)} = .0433$$

$$\frac{I_v}{d t^3} = 90 \qquad \text{Ref. Fig C 10.9}$$

$$I_v = 90 (10) \left(\overset{.005832}{.180^3}\right) = \underline{\underline{5.23}} \; in^4$$

Use 5 x 3½ x ¼ L,   I = 5.4 in⁴

Rivet Spacing = 10/4 = 2½"

$$NASB - 27'39$$

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

SHEAR WEB ANALYSIS (Cont'd)

MIDDLE BAYS - PANEL

$a = 100''$, $b = 12''$, $t = .10''$ $q = 2320 \frac{lbs}{in}$

Applied shear $\tau_{nominal} = \frac{2320}{.10} = 23,200 \ psi$

$$\frac{b}{(t\sqrt{K_s})} = \frac{12}{.10(\sqrt{5.35})} = \frac{12}{.10(2.31)} = 52.0$$

$\tau_{cr} = 13,000 \ psi$ Ref EM BI-M2-1, Fig. 2

$\rho = \dfrac{\tau - \tau_{cr}}{\tau + \tau_{cr}}$ Ref NACA TN 2661

$= \dfrac{23,200 - 13,000}{23,200 + 13,000} = .282$

$K = 0.434\left(\rho + \frac{1}{3}\rho^3\right)$.   Ref NACA TN 2661

$= 0.434\left(.282 + \frac{.282^3}{3}\right) = .126$

$\tau_{allowable} = 21,000 \ psi$ Ref EM BI-M2-1, Fig. 6

This is less than the applied shear; ∴ increase the gage to .110''.

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)
SHEAR WEB ANALYSIS (Cont'd)

MIDDLE BAYS — PANEL (Cont'd)

For $t = .110''$ $\qquad \tau = \dfrac{2320}{.110} = 21,000 \text{ psi}$

$$\dfrac{b}{(t\sqrt{K_s})} = \dfrac{12}{.110\sqrt{5.35}} = 47.3$$

$$\tau_{cr} = 15,000 \text{ psi} \qquad \text{Ref EM B1-M2-1, Fig 2}$$

$$\rho = \dfrac{\tau - \tau_{cr}}{\tau + \tau_{cr}} = \dfrac{6000}{36,000} = .167$$

$$K = 0.434 \left(.167 + \dfrac{.167^3}{3}\right) = .0732$$

$$\tau_{allowable} = 21,000 \text{ psi} \qquad \text{Ref EM B1-M2-1, Fig 6}$$

$$\text{OK.}$$

$K = $ "Diagonal Tension Factor" which
Varies from 0 to 1.0;
$\qquad$ 0 for shear resistant webs,
$\qquad$ 1.0 for pure diagonal tension webs.

$$\underline{NAS\ 8-27739}$$

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)
SHEAR WEB ANALYSIS (Cont'd)

MIDDLE BAYS - UPRIGHTS

$$\tau_{cr} = 15000\ psi = 15000 \times .110 = 1650\ \text{lbs/in}$$

$$\tau - \tau_{cr} = 2320 - 1650 = 670\ \text{lbs/in}$$

Column load on stiffener

$$P_{stiff} = 670 \times \cos 40° \times 12 = 6160\ \text{lbs}$$

Tension field angle assumed
to be 40° (conservative)
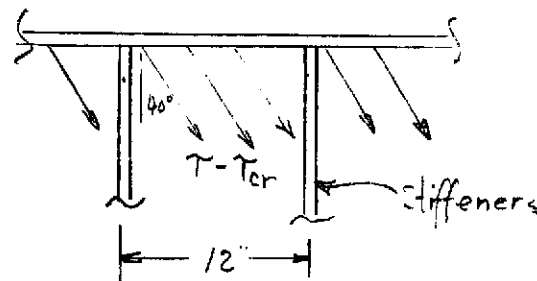
Using the same upright
as in the adjacent shear-resistant bay;
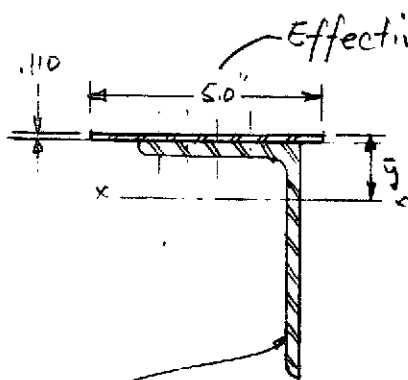
Effective width of .110 panel.

$$A = 2.06 + .55 = 2.61\ \text{in}^2$$

$$\bar{y} = \frac{2.06(1.67) + .55(.055)}{2.61} = .32$$

$$I_{xx} = 2.06(1.67^2) + 5.4 - 1.33(.347) = 6.52\ \text{in}^4$$

$$\rho = \left(\frac{6.52}{2.61}\right)^{1/2} = 1.58$$

$5 \times 3\frac{1}{2} \times \frac{1}{4} \angle$

$I_{ox} = 5.4\ \text{in}^4 \qquad y = 1.56\ \text{in}$

$A = 2.06\ \text{in}^2 \qquad \rho = 1.61\ \text{in}$

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)
SHEAR WEB ANALYSIS (Cont'd)
MIDDLE BAYS - UPRIGHTS (Cont'd)

$$\frac{L'}{\rho} = \frac{100}{1.58} = 63.4$$

$F_{co} = 31.0 \text{ KSI}$ Ref. fig 3A, p 11A

$$f_{co} = 6160/2.61 = 2360 \text{ psi}$$

$$f_{be} = \frac{6160(1.33)(1.33)}{6.52} = 1670 \text{ psi}$$

$$f_{co} + f_{be} = 2360 + 1670 = 4030 \text{ psi} \qquad OK.$$

RIVET SPACING

Check spacing at $s = b/4 = 12/4 = 3"$

Load per rivet = $2320(.3) = 6960$ lbs   Too high

@ 1" spacing, rivet load = 2320 lbs

Use 1/4" monel or equiv titanium rivet.

Shear strength of 1/4" ϕ rivet = 2540 lbs
Ref MIL-HDBK 5
OK

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THRUST STRUCTURE SHEAR WEB BEAM. (Cont'd)

SHEAR WEB ANALYSIS (Cont'd)

MIDDLE BAYS - UPRIGHTS (Cont'd)

A check of column loading and forced crippling will be made using the methods presented in TN 2661, "A Summary Of Diagonal Tension, Part I - Methods of Analysis" by P. Kuhn, J.P. Peterson, & L.R. Levin

Effective area of upright:

$$A_{U_e} = \frac{A_u}{1 + \left(\frac{e}{\rho}\right)^2} \qquad (TN\ 2661,\ p\ 4.)$$

$$= \frac{2.06}{1 + \left(\frac{1.615}{1.61}\right)^2} = \frac{2.06}{2.0} = 1.03 \ in.^2$$

Average stress in upright:

$$\frac{A_{U_e}}{dt} = \frac{1.03}{12(.110)} = .780$$

$$\frac{\sigma_u}{\tau} = .06 \quad for \ K = .0732 \quad (TN\ 2661,\ fig\ 14)$$

$$\sigma_u = .06(21,000) = 1260 \ psi$$

This is the average stress in the median plane of the web-attach leg of the angle.

$$\underline{NAS\,8-27739}$$

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)
SHEAR WEB ANALYSIS (Cont'd)
MIDDLE BAYS — UPRIGHTS (Cont'd)

Maximum stress in upright: (At midheight)

$$\frac{\sigma_{u_{max}}}{\sigma_u} = 1.66 \quad for \quad \frac{d}{h_u} = \frac{12}{100} = .12 \quad (TN\ 2661\ fig.\ 15)$$

$$\sigma_{u_{max}} = 1.66\,(1260) = 2090\ psi$$

Allowable stress in upright:

Effective Column length

$$L_e = \frac{h_u}{\sqrt{1 + K^2\left(3 - 2\frac{d}{h_u}\right)}} \quad for \quad d < 1.5h \quad (TN\ 2661\ p.\ 46)$$

$$= \frac{100}{\sqrt{1 + .0732^2\left(3 - 2\left(\frac{12}{100}\right)\right)}} \cong 100$$

$$\frac{L_e}{\rho} = \frac{100}{1.61} = 62.1$$

$$F_{co} = 31,100\ psi \qquad Ref.\ p.\ 11A,\ fig\ 3A\ OK.$$

$$\sigma_{u_{ave}} = \frac{\sigma_u A_{u_e}}{A_u} = \frac{1260\,(1.03)}{2.06} = 630\ psi$$

$$\frac{h_u}{2\rho} = \frac{100}{2(1.61)} = 31$$

$$F_{co} = 33,500\ psi \qquad Ref.\ p\ 11A,\ fig\ 3A \qquad OK.$$

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

SHEAR WEB ANALYSIS (Cont'd)

MIDDLE BAYS — UPRIGHTS (Cont'd)

Forced crippling check of web-attach flange:

Allowable $\sigma_o = 21,000 \, k^{2/3} \left(t_u / t \right)^{1/3}$ (TN 2661, p 41)

$$= 21,000 (.0732)^{2/3} \left(\frac{.25}{.110} \right)^{1/3} =$$

$$= 21,000 (.175)(1.315) = 4830 \text{ psi}$$

$\sigma_{u_{max}} = 2090 \text{ psi}$ Ref. p. 9B

$\sigma_{u_{max}} < \sigma_o$ $\therefore$ OK.

Tensile strength requirement of upright-to-web attach rivets:

Strength per inch run of rivets $> 0.22 \, t \, \sigma_{ult}$

$> 0.22 \, (.110)(\text{rivet tensile strength})$

$> .0232 \, (T)$

NAS8-27729

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

CAP ANALYSIS

UPPER CAP

Cap Load = 602 Kips Tension at mid-span
331 " " " 60" from ends
0 " at ends

Ref p 3

Tensile areas req'd:

At midspan, $\frac{602}{40}$ = 15.05 in²

" 60" , $\frac{331}{40}$ = 8.28 in²

$\left(\begin{array}{l} F_{tu} = 40 \text{ KSI} \quad \text{Ref MIL-HDBK-5} \\ F_{ty} = 27 \text{ " } \quad \text{Bars Rods & Shapes} \end{array} \right)$
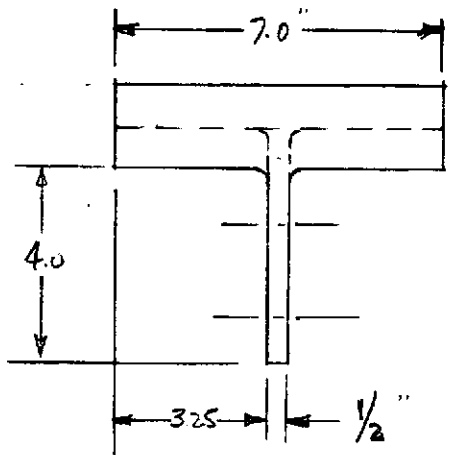
CAP THICKNESS = .9 @ 60"
A_{60} = 7.0 × .9 + .5 × 4.0 = 8.3 in²

CAP THICKNESS = 1.9" @ MIDSPAN
A = 7.0 × 1.9 + .5 × 4.0 = 15.3 in²

At ends, make cap thickness

= .50 in

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NAS 8-27739

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

CAP ANALYSIS – UPPER CAP (Cont'd)

Bending stresses in cap due diagonal tension:

$$M_{max} = K C_3 \frac{Sw \, d^2 \tan \alpha}{12 h} \qquad (TN \ 2661, \ p \ 50)$$

$$= .0732 (1.0) \frac{2320 (100)(12^2)(1.0)}{12 (100)}$$

C_3 assumed = 1.0
α approximated @ 45°

$$= 2040 \ \text{in-lbs}$$

Section modulus of Cap ≥ 5

$$f_b = \frac{2040}{5} = 408 \ \text{psi}$$

Negligible

NAS 8-27739

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)
CAP ANALYSIS (Cont'd)

LOWER CAP

CAP LOADS = 657 KIPS Compression at midspan
502 " " " 60" from right end
165 " " " right end
331 " " " 60" from left end
0 " " " left end.

Ref p. 3

Design Mech. properties of extrusions:

$$F_{tu} = 40 \text{ KSI}$$
$$F_{ty} = 27 \text{ "}$$
$$F_{cy} = 27 \text{ "}$$
$$E = 42.5 \times 10^6 \text{ psi}$$

Ref MIL·HDBK 5

Recent information from K.B.I (Vendor) is that $F_{ty} = F_{cy} = 35$ KSI minimum due to advances in extruding techniques and equipment. Therefore this value will be used in this analysis.

FIG 3A COLUMN BUCKLING CURVE
THICK BERYLLIUM EXTRUSIONS

This curve extrapolated from
EM 81-M2-1 for $F_{cy} = 35$ KSI.

RT.

F_{co} (10^3 psi)

l/ρ

L-18,

SK2 201020 PAGE 11A EM 81-M2-9

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

CAP ANALYSIS (Cont'd)

LOWER CAP (Cont'd)

Trial Section At Midspan
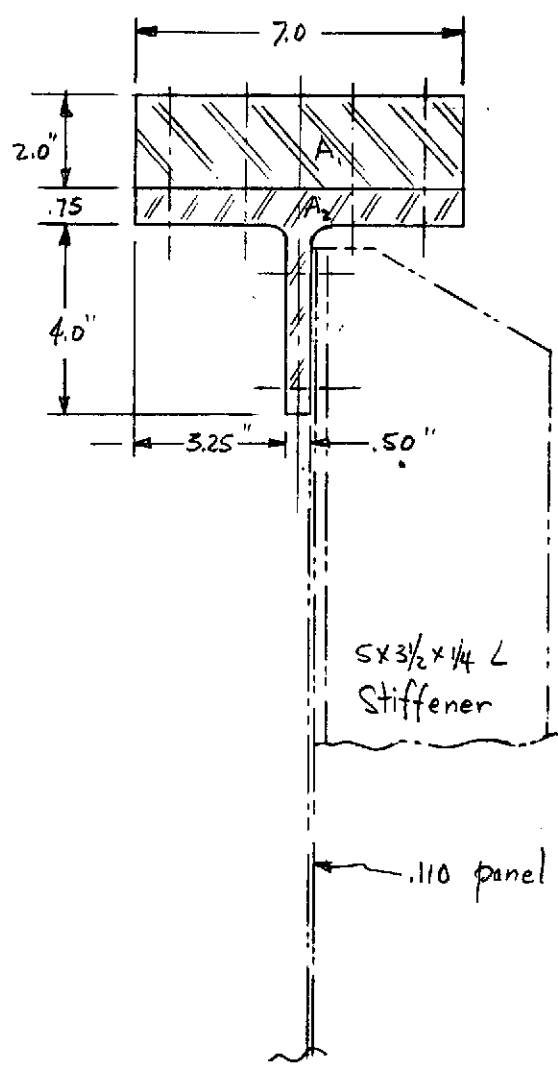
$A_1 = 7.0 \times 2.0 = 14.0 \ in^2$

$A_2 = 7.0 \times .75$
$\quad + 4.0 \times .50 = \underline{7.25}$ "
$\quad\quad\quad TOTAL = \overline{21.25 \ in^2}$

$I_{y-y} = \dfrac{2.75(20^3)}{12} = \dfrac{2.75(342)}{12}$

$\quad\quad\quad = 78.3 \ in^4$

$\rho = \left(\dfrac{78.3}{21.25}\right)^{1/2} = 1.92 \ in$

$\dfrac{L'}{\rho} = \dfrac{120}{1.92} = 62.5$

$F_{co} = 31.0 \ KSI$

Ref EM B1-M2-1
interpolated for
$F_{cy} = 35 \ KSI$
Fig 3A, p. 11A

$f_c = \dfrac{657}{21.25} = 31.0 \ KSI.$ Section OK.

$$\underline{NAS\ 8-27739}$$

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

LOWER CAP ANALYSIS (Cont'd)

Trial Section at 60" from right end.
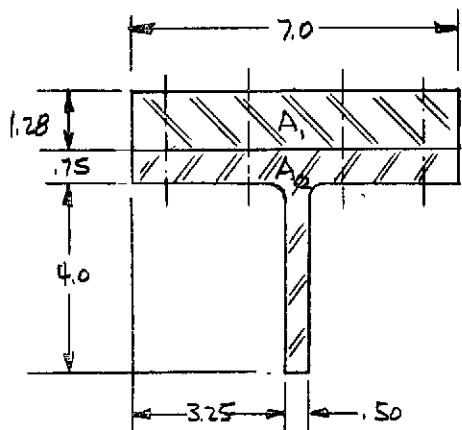
$A_1 = 7.0 \times 1.28 = 8.95$ in^2

$A_2 = 7.0(.75) + 4.0(.5) = 7.25$ "

Total Area $= 16.20$ in^2

$$I_{yy} = \frac{2.03(7.0^3)}{12} = \frac{2.03(342)}{12}$$

$$= 57.8 \text{ in}^4$$

$$\rho = \left(\frac{57.8}{16.20}\right)^{1/2} = 1.89 \text{ in}$$

For $L' = 60"$,

$$L'/\rho = \frac{60}{1.89} = 31.8$$

$$F_{co} = 33.2 \text{ KSI}$$

For $L' = 120"$,

$$L'/\rho = \frac{120}{1.89} = 63.5$$

$$F_{co} = 31.0 \text{ KSI}$$

$$f_{co} = \frac{502}{16.2} = 31.0 \text{ KSI} \qquad \text{OK.}$$

Section at right end
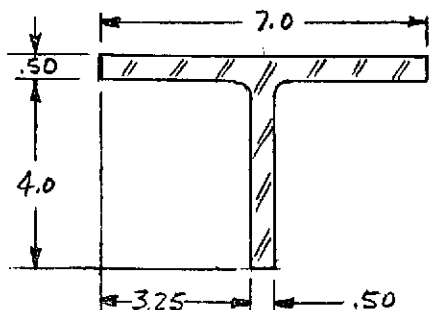
$A = 7.0(.50) + 4.0(.50) = 5.5$ in^2

$$I_{yy} = \frac{.50(7.0^3)}{12} = \frac{.5(342)}{12} = 14.2 \text{ in}^4$$

$$\rho = \left(\frac{14.2}{5.5}\right)^{1/2} = 1.57 \text{ in} \qquad L'/\rho = \frac{60}{1.57} = 38.2$$

$$F_{co} = 33 \text{ KSI.} \qquad f_{co} = \frac{165}{5.5} = 30.0 \text{ KSI} \qquad \text{O.K.}$$

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L-20

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

LOWER CAP ANALYSIS (Cont'd)

Section at 60" From Left End
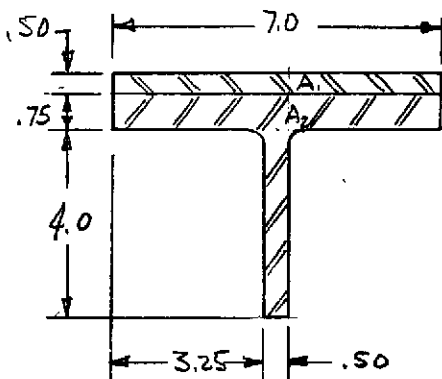
$A_1 = .50 \times 7.0 = 3.50$

$A_2 = .75 \times 7.0 + .50 \times 4.0 = \underline{7.25}$

$\text{TOTAL} = 10.75 \ in^2$

$I = \frac{1.25(7.0^3)}{12} = \frac{1.25(342)}{12} = 33.7 \ in^4$

$\rho = \left(\frac{33.7}{10.75}\right)^{1/2} = 1.77$

$L'/\rho = \frac{120}{1.77} = 67.8 \qquad F_{co} = 31.0 \ KSI$

$f_{co} = \frac{331}{10.75} = 30.8 \ KSI \qquad O.K.$

Section at left end.

Use same section as right end.

$A = 5.5 \ in^2. \qquad p. \ 13$

NAS8-21739

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

END POSTS AND THRUST POSTS

End posts and thrust posts (intermediate posts) will be designed to be machined from steel forgings.

4130 Steel @ 150 KSI H.T.

$F_{tu} = 150$ KSI $F_{bru} (e/D = 2) = 287$ KSI

$F_{ty} = 132$ " $F_{bry} (e/D = 2) = 218$ "

$F_{cy} = 145$ " $E = 29 \times 10^6$ psi

$F_{su} = 90$ "

Ref MIL-HDBK-5 properties.

NAS8-27739

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

END POSTS & THRUST POSTS (Cont'd)

STABILITY REQUIREMENT

For a uniformly distributed load on a Column,

$$(qL)_{cr} = \frac{7.84 \, EI}{L^2}$$

Ref. Timoshenko & Gere, "Theory of Elasticity"

$$I_{req'd} = \frac{q \, L^3}{7.84 \, E}$$

$E = 29 \times 10^6 \; psi$

$7.84 \, E = 227 \times 10^6$

L (in)	q (lbs/in)	$I_{req'd}$ (in4)	q (lbs/in)	$I_{req'd}$ (in4)	q (lbs/in)	$I_{req'd}$ (in4)
10	5620	24.8×10^{-3}	3300	14.6×10^{-3}	4530	20×10^{-3}
20	↑	.198	↑	.116	↑	.160
30		.670		.393		.540
40		1.59		.930		1.28
50		3.10		1.82		2.50
60		5.35		3.14		4.32
70		8.48		4.97		6.83
80		12.65		7.45		10.25
90	↓	18.10	↓	10.6	↓	14.6
100	5620	24.8	3300	14.6	4530	20.0

$$\underline{NAS\ 8-27739}$$

THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

END POSTS & THRUST POSTS (Cont'd)

STABILITY REQ'MENT CHECK

For a pinned end column,

$$P_{cr} = \frac{\pi^2 E I}{\ell^2}$$

For $P = 562$ KIPS, $\ell = 100$, $E = 29(10^6)$

$$I_{req'd} = \frac{562,000\ (100^2)}{\pi^2\ (29)(10^6)} = 19.7\ in^4$$

For $P = 330$ KIPS, $\ell = 100$

$$I_{req'd} = \frac{330,000\ (100^2)}{\pi^2\ (29)(10^6)} = 11.5\ in^4$$

For $P = 453$ KIPS, $\ell = 100$,

$$I_{req'd} = \frac{453,000\ (100^2)}{\pi^2\ (29)(10^6)} = 15.9\ in^4$$

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THRUST STRUCTURE SHEAR WEB BEAM (Cont'd)

END POSTS & THRUST POSTS (Cont'd)
ROOM TEMPERATURE
COLUMN ALLOWABLE STRESSES
FOR 4130 STEEL @ 150 KSI H.T.

$K = .0225$, $n = 45$, $F_{0.7} = 145.2$ KSI
(Ref LAC SM 80)

$F_{co} \sim$ KSI (vertical axis): 160, 140, 120, 100, 80, 60, 40, 20, 0

L/ρ inches (horizontal axis): 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140

145.2
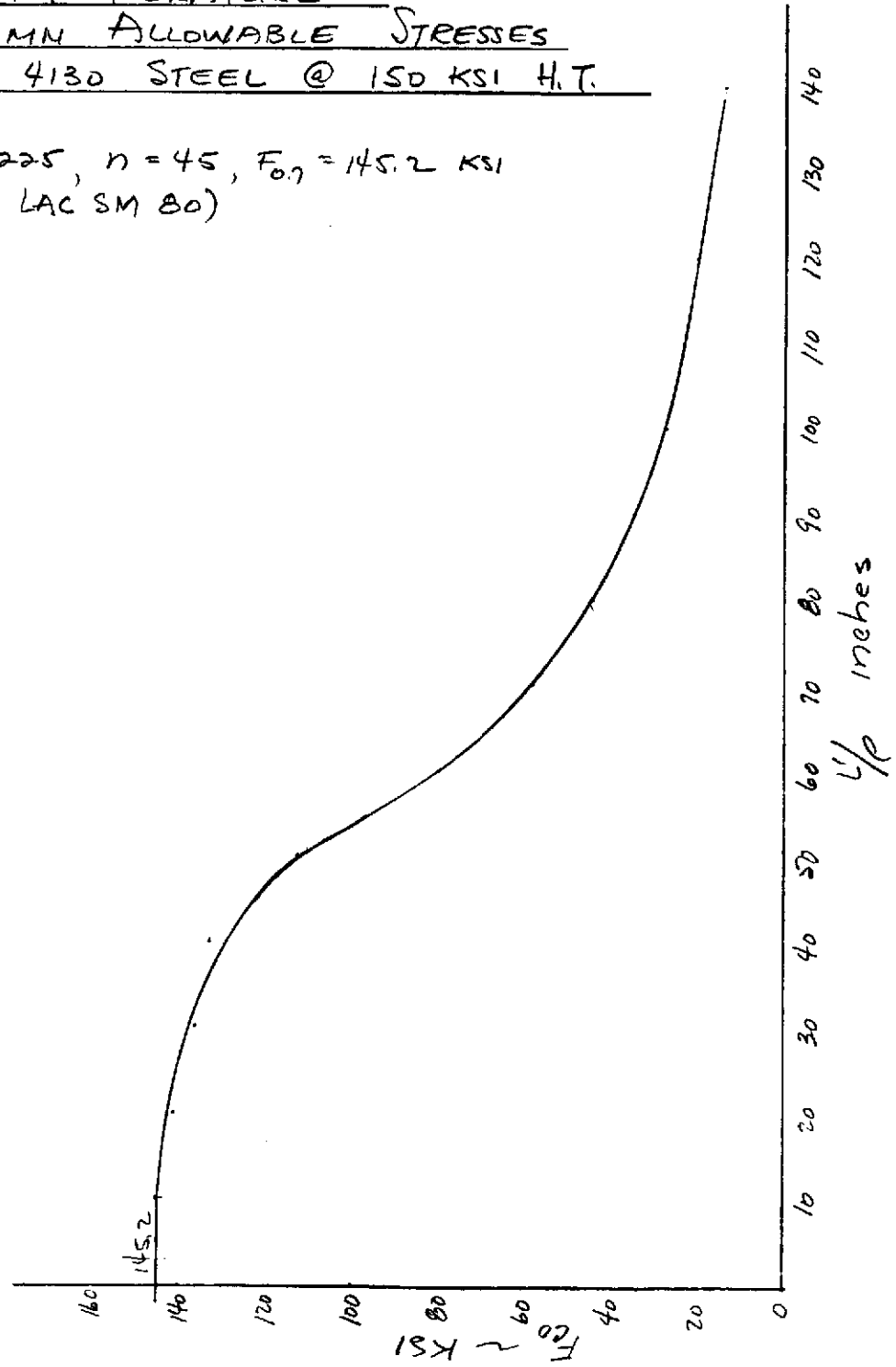
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Appendix M

EM B1-M2-10

WEIGHT COMPARISON OF CANDIDATE MATERIALS FOR UNIFORM LOAD PANEL

Lockheed Missiles & Space Company   Space Shuttle Project

ENGINEERING MEMORANDUM

TITLE: WEIGHT COMPARISON OF CANDIDATE MATERIALS FOR UNIFORM LOAD PANEL	EM NO: B1-M2-10
	REF:
	DATE: 1 August 1972
AUTHORS: C. C. Richie	APPROVAL:
	ENGINEERING
	SYSTEM ENGRG

PROBLEM STATEMENT

Perform a weight comparison of candidate materials for the uniform load panel developed on NASA/MSFC Contract NAS 8-27739, "Evaluation of Beryllium for Space Shuttle Components".
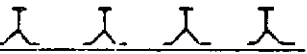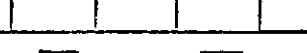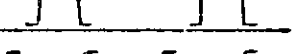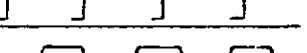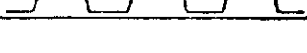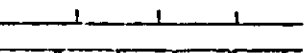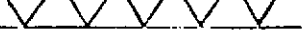
RESULTS

Optimum uniform load panel dimensions and unit weights are summarized in Tables 2 and 3, respectively.

Based on the specified panel design conditions, the least weight candidate material for the uniform load panel was beryllium. Relative to beryllium, unit panel weights for boron aluminum, aluminum, titanium, and steel indicate weight penalties of 8 percent, 100 percent, 170 percent and 260 percent, respectively.

ANALYSIS

1.0 Panel Optimization Method

Based on wide column optimization procedures presented in Reference (1), a weight efficiency comparison of several panel configurations are shown below:

Configuration	ϵ	Percent Weight Penalty
(1)	1.60	Base
(2)	1.23	14
(3)	1.15	18
(4)	1.03	25
(5)	1.00	27
(6)	0.93	31
(7)	0.91	33
(8)	0.69	52
(9)	0.66	56
(10)	0.605	62

Based primarily on manufacturing and cost considerations, the zee-stiffened configuration (7) was selected for the uniform load panel. The panel cross section is optimized such that local and general instability failure modes occur simultaneously. The resulting equation for minimum weight is

$$\frac{N}{L\ \bar{\eta}\ E} = \epsilon\ \frac{(\bar{t})^2}{(L)}$$

where

N = compressive line load, LB/IN

L = panel length, IN

E = elastic modules, LB/IN^2

$\bar{t}$ = panel equivalent thickness, IN

ϵ wide-column efficiency

$\bar{\eta}$ plasticity correction factor

Plasticity correction factors are based on the Ramberg and Osgood three-parameter representation of stress-strain relations in the yield region.

Uniform load panel optimization was accomplished using the Z-STIFF computer code. Based on wide column theory presented in reference (1), the Z-STIFF computer code calculates panel equivalent thicknesses, dimensions, compressive buckling line load, allowable burst/collapse pressure, general shear buckling line load, and local shear buckling line load. Including beam column effects, allowable loads under combined compression, bending, and shear are computed from load interation equations.

2.0 Panel Weight Evaluation

Properties of candidate materials for the uniform load panel are shown in Table 1 Design temperature of 600°F was selected for beryllium, boron aluminum, titanium and steel. The aluminum alloy design temperature was 300°F.

Properties required for weight evaluation of the uniform load panel include the material density and Ramberg-Osgood parameters, i.e., compressive yield strength, elastic modulus and shape factor.

Design ultimate compressive line load for the uniform load panel was Nx=7,200 LB/IN.. Panel length was L=80 IN.. Simply supported edge conditions were assumed.

Zee-stiffened panel equivalent thickness versus compressive line load for candidate materials at elevated temperature are shown in Figure 1.

Except for beryllium, the candidate materials display linear elastic behavior for compressive line loads less than Nx=10,000 LB/IN. Because of relatively low compressive yield strength, beryllium plastic behavior begins to occur at approximately Nx=2,500 LB/IN..

Optimum uniform load panel dimensions and unit weights are summarized in Tables 2 and 3, respectively. Based on the specified panel design conditions, the least weight candidate material for the uniform load panel was beryllium. Relative to beryllium, unit panel weight for boron aluminum involves an 8-percent weight penalty. As shown in Table 3, relative panel weights for aluminum, titanium, and steel indicate weight penalties of 100 percent, 170 percent and 260 percent, respectively.

REFERENCES

1. Emro, D. H., Spunt, L., "Wing Box Optimization Under Combined Shear and Bending", AIAA Journal of Aircraft, Vol. 3, No. 2, March - April 1966

TABLE 1

PROPERTIES OF CANDIDATE MATERIALS AT ELEVATED TEMPERATURE

MATERIAL	CONDITION		THICKNESS, IN, OR AREA, IN^2	GRAIN	BASIS	η	F_{cy}, KSI	E, PSI $\times 10^6$	ρ LB/IN^3
BERYLLIUM, SHEET , (2)	RT	CROSS ROLLED	0.020- 0.375			35	55	42.0	0.067
	600 °F					35	43	37.2	
BORON ALUMINUM, UNI-DIRECTIONAL, (3)	RT			L		20	180	32.0	0.096
	600°F					20	171	30.1	
ALUMINUM ALLOY, 7075 SHEET , (1)	RT	-T6	0.012- 0.039	L	B	15	71	10.5	0.101
	300 °F					15	59	10.0	
ALUMINUM ALLOY, 2024 SHEET , (1)	RT	-T81	0.010 - 0.249	L	B	20	61	10.9	0.100
	300 °F					20	61	10.0	
TITANIUM 6Al - 4V , (4)	RT	STA	$t \leq 0.187$	L	B	20	157	16.4	0.160
	600 °F					15	102	14.0	
STEEL AM 350 , (1)	RT	DA	$t \leq 0.187$	L	S	15	142	29.0	0.282
	600 °F					15	118	25.5	

REFERENCES : (1) MIL-HBK-5B   (2) CALAC, "ADVANCED MATERIALS HANDBOOK"
(3) "STRUCTURAL DESIGN GUIDE FOR ADVANCED COMPOSITE APPLICATIONS", SOUTHWEST
RESEARCH INSTITUTE   (4) CALAC STRESS MEMO MANUAL , NO. 836

Header: C. C. RICHIE

Y-axis label: PANEL EQUIVALENT THICKNESS, $\bar{t}$, in^2/in — labeled $\bar{t}$-M-5

X-axis label: COMPRESSIVE LINE LOAD, N_x, Lb/in

Axis values: 10, 100, 1000, 10,000

LEGEND:
- STEEL, AM-350, T = 600°F
- TITANIUM, 6AL-4V STA, T = 600°F
- ALUMINUM, 7075-T6, T = 300°F
- ALUMINUM, 2024-T81, T = 300°F
- BERYLLIUM, CROSS ROLLED, T = 600°F
- BORON ALUMINUM, T = 600°F

NOTES:
1) COLUMN LENGTH, L = 20 IN
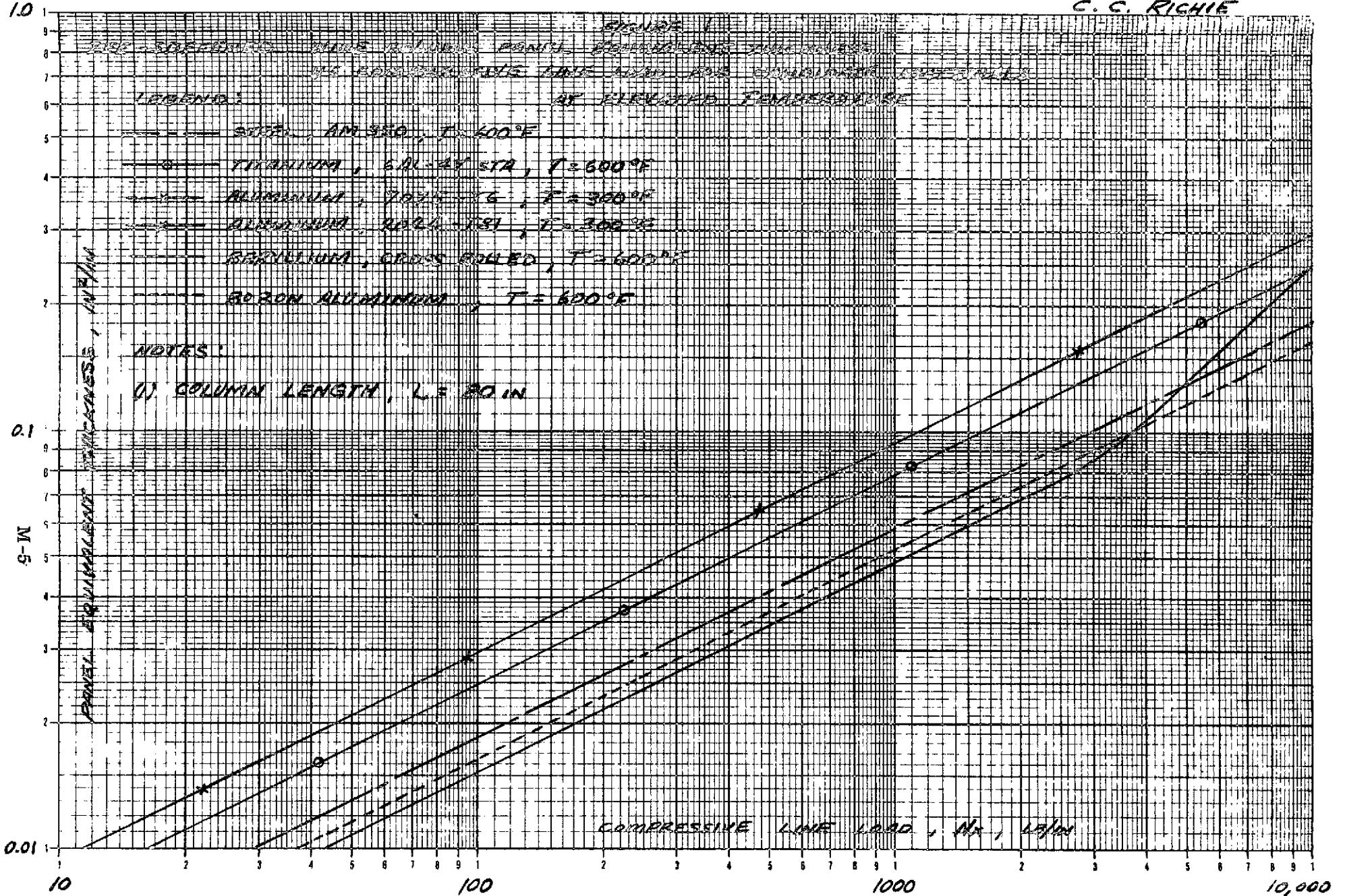
TABLE 2

OPTIMUM UNIFORM LOAD PANEL DIMENSIONS FOR CANDIDATE MATERIALS AT ELEVATED TEMPERATURE

MATERIAL AND DESIGN TEMPERATURE	EQUIV. THICKNESS $\bar{t}$, IN	DIMENSIONS					
		t_s, IN	b_s, IN	t_w, IN	b_w, IN	t_f, IN	b_f, IN
BERYLLIUM, CROSS ROLLED @ 600 °F	0.18630	0.07526	3.943	0.07977	3.431	0.07977	1.029
BORON ALUMINUM, UNI-DIRECTIONAL @ 600 °F	0.14056	0.05678	3.054	0.06019	2.657	0.06019	0.7972
ALUMINUM ALLOY, 7075 - T6 @ 300 °F	0.25146	0.10158	4.085	0.1077	3.554	0.1077	1.066
ALUMINUM ALLOY, 2024 - T81 @ 300 °F	0.25144	0.10158	4.085	0.1077	3.555	0.1077	1.066
TITANIUM, 6Aℓ-4V STA @ 600 °F	0.21251	0.08585	3.756	0.09099	3.268	0.09099	0.9802
STEEL, AM 350 @ 600 °F	0.15746	0.06361	3.233	0.06743	2.812	0.06743	0.8457

NOTES:

(1) ZEE STIFFENED WIDE COLUMN PANEL (REF. 1)

(2) COMPRESSIVE LINE LOAD N_x = 7,200 LB/IN

(3) PANEL LENGTH, L = 80 IN

DIMENSIONAL NOTATION:
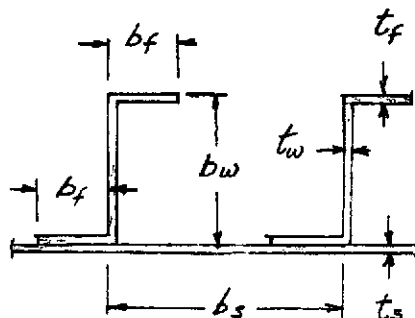
TABLE 3

SUMMARY OF OPTIMUM UNIFORM LOAD PANEL UNIT WEIGHTS FOR CANDIDATE MATERIALS AT ELEVATED TEMPERATURE

MATERIAL AND DESIGN TEMPERATURE	PANEL UNIT WEIGHT, W, LB/FT^2	RELATIVE PANEL WEIGHT
BERYLLIUM, CROSS ROLLED @ 600°F	1.797	1.000
BORON ALUMINUM UNI-DIRECTIONAL @ 600°F	1.943	1.081
ALUMINUM ALLOY, 2024-T81 @ 300°F	3.621	2.015
ALUMINUM ALLOY, 7075-T6 @ 300°F	3.657	2.035
TITANIUM, 6Al-4V (STA) @ 600°F	4.896	2.725
STEEL, AM 350 @ 600°F	6.394	3.558

NOTES:

(1) ZEE STIFFENED WIDE COLUMN PANEL (REF. 1)

(2) COMPRESSIVE LINE LOAD, $N_x = 7200$ LB/IN

(3) PANEL LENGTH, $L = 80$ IN

FORM LMSC 362B-3

Appendix N

EM B1-M2-11

COST EVALUATION OF
BERYLLIUM STRUCTURES

ENGINEERING MEMORANDUM

TITLE: COST EVALUATION OF BERYLLIUM STRUCTURES	EM NO: B1-M2-11
	REF:
	DATE: 1 August 1972
AUTHORS: H. D. Anderson	APPROVAL: ENGINEERING
	SYSTEM ENGRG

PROBLEM STATEMENT

Evaluate the manufacturing costs of beryllium structural components fabricated under Contract NAS 827739 and compare the costs with those of comparable structural designs using aluminum and titanium materials. Using cost sensitivities developed by LMSCI for various configurations of the Space Shuttle, show the value of a pound of weight saved in the vehicle primary structure.

RESULTS

The manufacturing costs of the beryllium panels and beams were determined to range from $227/lb to $313/lb in comparison to an average unit cost of $120/lb for comparable aluminum construction. Comparison of costs is also made on a basis of cost complexity factors published in the general literature. The value of a pound of weight saved in Space Shuttle primary structure was developed in the Ref 2 study, and is shown for the current configuration to be:

- Orbiter — 23,400 $/lb
- Tank — 16,500 $/lb
- Booster — 1,900 $/lb

DISCUSSION

Manufacturing costs for four prototype panels are developed in terms of cost per pound of structure. This unit cost approach permits a realistic comparison of costs with comparable aluminum aircraft structure manufacturing costs. Basic cost data on the four prototype panels are summarized in Table 1. The uniform load panel and concentrated load panel cost data are derived from basic information accumulated during the actual fabrication of these panels. The cost data shown for the shear web beam and truss beam are based on manufacturing labor estimates summarized in Table 2; these structures were designed in detail but were not fabricated.

Table 1

PROTOTYPE PANEL WEIGHT/COST DATA

Factor	Uniform Load Panel (SKJ-201002)	Concentrated Load Panel (SKC-201001)	Shear Web Beam (SKR-201020)	Truss Beam (SKR-201017)
Labor Hours	652	1,345	21,150	9,500
Labor Cost (at $28/hr)	18,250	37,700	592,000	266,000
Material Cost ($) [1]	7,779	11,262	186,036	177,428
Total Cost ($)	26,029	48,962	778,036	443,428
Panel Weight (lb)	83.3	163.1	2,773.0	1,954.0
Unit Cost ($/lb)	313	300	281	227
Beryllium Wt (lb)	51.0	72.6	1389.0	1347.0
Other Structure Wt (lb)	23.0[2]	70.6[2]	1273.0[3]	500.0[2]
Fastener Wt (lb)	9.3	19.9	111.0	107.0
Panel Complexity Factor[4]	2.72	2.60	2.13	2.74
Unit Cost Ratio[5]	2.61	2.50	2.34	1.89

(1) Beryllium at $150/lb (W < 100 lb) and $130/lb (W > 1000 lb); other material at $4/lb.

(2) Titanium

(3) Steel

(4) Calculated average factor based on panel weight breakdown, and first unit cost complexity factors from Table 3.

(5) Panel unit cost versus aluminum structure unit cost of $120/lb.

Table 2

MANUFACTURING LABOR ESTIMATES

Operations	Labor Hours			
	Shear Web Beam (SKR-201020)		Truss Beam (SKR-201017)	
Panel Fabrication		18,240		7,600
Parts Fab	11,910		4,670	
Sub-Assembly	—		580	
Final Assembly	1,600		380	
Contingency[1]	4,730		1,970	
Tool Fabrication		9,330		3,440
Templates	530		460	
Sub-Assembly Fixtures	800		800	
Major Fixtures	8,000		2,000	
Misc Tooling	—		180	
Planning		830		460
Tool Engineering		1,040		400
Quality Assurance		830		830
Manufacturing Coordination		210		210
Total:		30,480		12,940

(1) Contingency of 35% assumed for design changes and rework of parts, and for unknowns.

The panel unit costs ranging from \$227/lb to \$313/lb are to be compared to an average cost of \$120/lb for semimonocoque aluminum aircraft structure costs. The aircraft unit cost value is derived from actual first-unit cost data on Lockheed's L-1011 and C-5A programs. With these values as a basis for comparison, unit cost ratios ranging from 1.89 to 2.61 are provided, as shown in Table 1. These ratios are essentially the average manufacturing cost complexity factor for each of the panels, and can be compared to the panel complexity factors which are also listed in Table 1. The panel complexity factors are calculated by use of the panel weight breakdown given in the table and the first-unit cost complexity factors from Table 3. For example, the SKJ-201002 Uniform Load Panel complexity factor (neglecting fastener weight) is:

$$CF = \frac{51.0\ (2.9)\ +\ 23.0\ (2.3)}{74.0} = 2.72$$

Note that the values developed in each of the comparisons (unit cost ratios versus panel complexity factors) are in good agreement except for the SKR-201017 truss beam. The estimated costs for this structure are significantly lower, due primarily to the fact that appreciably less machining/drilling and forming are required in the manufacture of this type of structure than for the shear web beam and experimental panels.

The labor hours estimated for tool fabrication are excluded from panel costs shown in Table 1 for the shear web beam and truss beam. These costs should be amortized over the total production quantity, in which case the impact on unit cost per pound is much less. For example, the shear web beam tool fabrication costs are estimated at \$261,000 (9,330 x 28.0); this amounts to \$94/lb for one panel but only \$9.4/lb for ten panels. The exclusion of tool fabrication costs and inclusion of planning and tool engineering costs puts the costing of all four structures on a directly comparable basis for this cost evaluation.

The unit costs developed herein for the prototype panels are somewhat higher than would be expected for large production quantities where "learning" results in lower costs for recurring operations. In typical cost estimation practices, learning is not applied on test hardware but is applied on all production hardware. Learning rates of 90 percent and 95 percent are considered typical for structural components of the type evaluated in this study.

Table 3

COMPLEXITY FACTORS[1], FIRST UNIT COST

MATERIAL	MONOCOQUE	S/S/F[2] S/F [3]	CORRUGATION HONEYCOMB	STRUCTURAL SHAPE
ALUMINUM	0.6	1.0	1.4	1.0
STEEL (HS/SS)/HAYNES 188	0.8	1.3	1.9	1.3
BERYLLIUM	1.7	2.9	4.2	2.9
TITANIUM	1.1	2.3	3.8	2.1
INCO 718	1.5	2.9	4.7	3.0
L 605	1.8	3.1	4.6	3.1
RENE 41	1.1	2.2	3.7	2.0
HASTELLOY X	0.9	1.9	3.1	1.7
TD-NICKEL-CHROME	2.4	4.1	6.9	4.1
COATED COLUMBIUM	~6	~12	~17	~11
COATED TANTALUM	~8	~14	~19	~13
ALUMINUM COMPOSITES	~2.5	~4	~5.5	~4
TITANIUM COMPOSITES	~3	~5	~7	~5
GRAPHITE	~20	-	-	-

(1) TO BE USED FOR: AERODYNAMIC SURFACES   (2) SKIN/STRINGER/FRAME
                        BODY/TANK STRUCTURE   (3) SKIN/FRAME
                        THERMAL PROTECTION SYSTEM PANELS
                        DROPTANKS

Though the data are limited, experiences on this program indicate that forming, cutting, and drilling of beryllium are less difficult, in the gages used, than the equivalent operations in titanium. This may also be seen in the following example:

	Al	Ti	Be
Complexity Factor (Table 3)	1.0	2.3	2.9
Unit Cost ($/lb)	120	276	348
Material Cost ($/lb)	1	4	130
Labor Cost ($/lb)	119	272	218
Labor Unit Cost Ratio	1.00	2.28	1.83

The lower value of labor unit cost developed for beryllium (1.83 vs 2.28) in this arbitrary example also indicates that titanium is appreciably more difficult to work with.

The difficulty of working with titanium was studied extensively in an experimental program performed by the Lockheed-California Company during the SST Development Phase II-B Program. Fabrication costs were developed in a study of over 500 parts, comparing the costs of various operations in making identical parts using aluminum and titanium materials. The data were reduced to complexity factors as tabulated in Table 4.

Table 4

COMPLEXITY FACTORS FOR TITANIUM VS ALUMINUM STRUCTURE

Fab/Assy Labor	Complexity Factor	
	Ti	Al
Skin Fab W/O Forming	2.6	1.0
Simple Hot Form	2.8	1.0
Average Hot Form	3.3	1.0
Complex Hot Form	4.2	1.0
Machining and Drilling	6.7	1.0
Assembly (Gauge $\lesssim$ 0.060)	3.0	1.0
Assembly (Gauge 0.060-0.125)	4.0	1.0

Note that the average value of 2.3 for titanium given in Table 3 is lower than any of the factors listed in Table 4 for specific fabrication operations. It must be noted however that the study results given in Table 4 were developed from a different base and have a different application than the factors given in Table 3.

Although beryllium/titanium structures are appreciably higher than aluminum in direct manufacturing costs, the weight saved is frequently an important factor in reducing overall program or operating costs. LMSCI's studies of alternate Space Shuttle concepts have included a number of structural design/cost trade studies (see Refs 1 and 2) where the design options were evaluated in terms of total program costs. The data in Table 5, taken from the Ref 2 study, show that for typical Space Shuttle launch configurations the value of a pound of weight saved in the orbiter vehicle is on the order of $14,500/lb to $23,400/lb during the design phase when the external tank and booster can be resized to accommodate orbiter weight changes. This potential savings in total program costs should be considered along with direct manufacturing costs when selecting material and construction methods for orbiter structural components.

REFERENCES

1. H. D. Anderson, "Orbiter Airframe Structural Design Options and Their Impact on Space Shuttle Program Costs," LMSC EM No. L4-01-01-03-M2-7, 26 October 1971

2. "Space Shuttle Cost and Weight Sensitivity Study," (First Technical Progress Report), LMSC-D153524, 1 June 1972

Table 5

CONCEPT SENSITIVITY COMPARISON

Δ INPUT WEIGHT (FREE)	STAGE-AND-ONE-HALF		TWO STAGE		RAO	
	Δ GROSS WT / Δ INPUT WT	Δ PROG COST / Δ INPUT WT	Δ GROSS WT / Δ INPUT WT	Δ PROG COST / Δ INPUT WT	Δ GROSS WT / Δ INPUT WT	Δ PROG COST / Δ INPUT WT
ORBITER (LB)	26	$14,500	42	TBD	46	$23,400
TANK (LB)	11	$5,500	-	-	32	$16,500
BOOSTER (LB)	-	-	9.4	TBD	4.2	$1,900
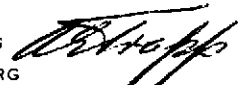
Appendix O

EM B1-M3-1

PROCESS DEVELOPMENT
EVALUATION PLAN

ENGINEERING MEMORANDUM

TITLE: 3.2 Process Development Evaluation Plan	EM NO: B1-M3-1
	REF:
	DATE: 23 August 1971
AUTHORS: S. H. Lee	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Identify those process development activities to be conducted and the methods by which the attendant results will be evaluated. All development tasks will be designed to define specific fabrication characteristics related to the large compression panels and truss beams required by this program. These structures can be considered as typical structures identified with space shuttle.

This evaluation plan is a part of Phase III, Process Technology Development of Contract NAS-8-27739 titled "Evaluation of Beryllium for Space Shuttle Components."

RESULTS

The scope of this contract is directed towards the development of material properties, process technology and design limitations on the potential applications of beryllium to space shuttle structures under reuse conditions. The investigative analyses are to be verified with testing of certain structural components and assemblies. The types of structures to be considered are:

1. Compression Panel for 600°F Operation
2. Panel With Concentrated Load for 600°F Operation
3. Truss Beam for 200°F Operation
4. Shear Web Beam for 200°F Operation

The candidate structural component and assembly designs will utilize primarily cross-rolled beryllium sheets combined with only a limited amount of Ti-6Al-4V alloy sheets. To manufacture these designs, specialized sheet metal fabrication processes will be required. Standard sheet metal equipment and techniques must be modified and refined to cope with the unique characteristic of cross-rolled beryllium sheets. Configurations and sizes of the candidate test structures will involve the following fabrication processes:

- Mechanical cutting, routing and deburring
- Mechanical drilling
- Electrical (spark) machining
- Chemical etching (with or without electrical energy)
- Surface cleaning and preparation
- Thermal forming
- Riveting
- Mechanical joining
- Fluxless brazing

Existing LMSC capabilities related to the above are discussed in the attached document in order to identify the areas in which extended capabilities need to be developed. The development task details, the output desired and the approaches with which the outputs will be evaluated are also included in this plan.

PROCESS DEVELOPMENT EVALUATION PLAN

for
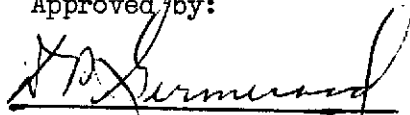
NASA Contract NAS8-27739

EVALUATION OF BERYLLIUM FOR SPACE SHUTTLE COMPONENTS

23 AUGUST 1971
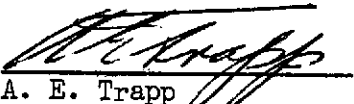
Approved by:

J. F. Milton, Director
Manned Space Programs

Prepared By: S. H. Lee
S. H. Lee
Phase III Task Leader

Approved By: A. E. Trapp
A. E. Trapp
Program Manager

Prepared for George C. Marshall Space Flight Center
by Manned Space Programs, Space Systems Division

LOCKHEED MISSILES & SPACE COMPANY

CONTENTS

LOCKHEED MISSILES & SPACE COMPANY

OBJECTIVE

The objective of this plan is to identify those process development activities
to be conducted and the methods by which the attendant results will be evalu-
ated. All development tasks will be designed to define specific fabrication
characteristics related to the large compression panels and truss beams required
by this program. These structures can be considered as typical structures
identified with space shuttle. Along with the background of experience exist-
ing at Lockheed, the process developed will be used to fabricate test components
and assemblies. When validated by test results, these process techniques will
further extend the applicability of beryllium in the Space Shuttle Program.

INTRODUCTION

This evaluation plan is a part of Phase III, Process Technology Development of
Contract NAS-8-27739 titled "Evaluation of Beryllium for Space Shuttle Com-
ponents." The scope of this contract is directed towards the development of
material properties, process technology and design limitations on the potential
applications of beryllium to space shuttle structures under reuse conditions.
The investigative analyses are to be verified with testing of certain structural
components and assemblies. The types of structures to be considered are:

1. Compression Panel for 600°F Operation
2. Panel With Concentrated Load for 600°F Operation
3. Truss Beam for 200°F Operation
4. Shear Web Beam for 200°F Operation

Structural analyses, Phase II, will be conducted on each type of structure
based on material properties to be developed in Phase I. Discrete components
will be fabricated and tested destructively as required to support analyses and
design. One each of the compression panels, type 1 and 2, will be fabricated
for testing by NASA at MSFC. Components for the structural assemblies will be
tested at LMSC.

1. PROCESS REQUIREMENTS

The candidate structural component and assembly designs will utilize primarily
cross-rolled beryllium sheets combined with only a limited amount of Ti-6Al-4V
alloy sheets. To manufacture these designs, specialized sheet metal fabrication
processes will be required. Standard sheet metal equipment and techniques must

be modified and refined to cope with the unique characteristic of cross-rolled beryllium sheets. Configurations and sizes of the candidate test structures will invoke the following fabrication processes:

- Mechanical cutting, routing and deburring
- Mechanical drilling
- Electrical (spark) machining
- Chemical etching (with or without electrical energy)
- Surface cleaning and preparation
- Thermal forming
- Riveting
- Mechanical joining
- Fluxless brazing

Existing LMSC capabilities related to the above are discussed herein in order to identify the areas in which extended capabilities need to be developed. The development task details, the output desired and the approaches with which the outputs will be evaluated are also included in this plan.

2. EXISTING CAPABILITIES

Within the various production areas for beryllium fabrication at LMSC, basic capability of those processes listed exist. As one of the largest users of beryllium in its many forms, LMSC has acquired and maintained a versatile capability in terms of facilities, techniques and skills for the design and fabrication of small-to-medium size beryllium structures. To fabricate large size structures such as those specified for this contract will require certain extensions and refinement of existing capability in some areas. Specifically, ability to accurately form long slender channel sections without distortion. acceptable fit tolerance for fastener clusters and fluxlessly brazed long tubular sections. Rationale for these needs are identified in the following description of LMSC's capabilities.

Of those processes required, several techniques can be common to one of the four (4) basic fabrication tasks; namely:

- Material Removal
- Forming
- Joining
- Finishing

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For example, chemical etching can be used either to remove material, prepare surfaces or stress relieve. On the other hand, each fabrication task could be accomplished by anyone of several process techniques. Mechanical machining, manual deburring, electrical machining and chemical machining, each can be used to remove material. The specific technique to be used is dependent on the configuration and/or the fabrication scheme involved.

2.1 Capability Descriptions

The following process capabilities are located under one roof in Building 170 of the Sunnyvale Complex encompassing 72,000 sq. ft. floor area and is specifically designated for beryllium fabrication. This building is equipped with a system of ventilation controls to eliminate the toxic hazards associated with beryllium fabrication. All operations capable of producing respirable airborne particles or mists of beryllium or its compounds are performed with exhaust ventilation adequate to keep the exposure of workers below the recommended threshold limits. Evacuation of undesirable particles are accomplished via either:

    a.   Close-capture, high velocity exhaust hoses held within one hose diameter from work.

    b.   Enclosures over the entire equipment.

    c.   Lateral slot exhaust at 250 cfm per sq. ft. of exposed surface area, such as liquid tanks.

In addition, individual workrooms are kept at a negative pressure with reference to the rest of the building. Integrity of this system is backed up by a standby system which can be cut in on demand.

2.1.1 <u>Mechanical Cutting, Routing and Deburring</u>
<u>Cutting</u> -

- Abrasive wheel (straight cuts) -
  14" diamond-bonded, diamond wheel with pressure-fed coolant system.
  Travel on an overhead rail. .20 to .50 1PM feed with 150 1PM
  rapid traverse.
  4" vertical adjustment cuts 2.0" thick plate work is stationary.
  96" max width 240" length or longer. Push button operation.

- Conventional Machining –

    A complement of more than 25 conventional engine lathes (up to
    32" swing), and milling machines equipped with carbide bits and
    cutters are readily available for this program.

Routing (curved cuts)

Stationary air motor-driven router spindles, free running at about 1000 RPM,
equipped with special carbide bits are available especially for beryllium.
Two basic types of router bits in use are: 1) multi-fluted spiral cut, and
2) standard diamond (burr) pattern. Work, rigidly supported in an appropriate
fixture, and guided by an appropriate router block is manually fed against the
stationary spindle at .5 to 1.0 1PM rate depending on the gage thickness.
Internal cutouts are made by slowly plunging a ball nose cutter through the
material, then progressing around the periphery of the cutout as guided by the
tooling. A flat nose-type cutter is used for outside edge trimming or shallow
scupturing partially through the material thickness. Current capability in-
cludes thickness up to .750" more than adequate for this program.

Deburring

- Radial arm abrasive wheel of various grid sizes in a clear plastic
    enclosure.
- Vacuum sanding box for hand-sanding, deburring and other related
    operations.
- Vapor honing chamber.

Existing facilities can handle a broad range of sizes and shapes of parts includ-
ing those anticipated for this program.

2.1.2 Mechanical Drilling

LMSC has a fully developed system of equipment, tooling and procedures for
accurately and reliably drilling holes in beryllium sheets. Special equipment
which consists of an automatic torque-sensing device that can vary both the
spindle speed and feed rate as necessary can maintain the cutting forces within
the safe limits of both the drill and the material. This device is set up to
use a special configured drill bit made of carboloy 883 or equivalent. This
system is capable of compensating for, within limits, the machineability of

the workpiece, the condition of the drill, and the break-through characteristics of the hole. This device is called the Tornetic System which was developed by Dyna Systems, Inc. in conjunction with LMSC's requirements. Many thousands of holes had been successfully placed in beryllium sheets and plates with this system. The special drills are being procured routinely under a tightly controlled procedure. LMSC has ample capability to meet any mechanical drilling requirements for this program.

2.1.3 Electrical (spark) Machining

Under certain conditions (non-circular, larger D/t, etc.), either mechanical drilling or routing may incur material damage because of the anisotropic grain structure of cross-rolled beryllium sheets. Electrical-discharge-machining (EDM) is often the only effective machining technique to be used. This process removes material by means of electrical discharges from tool to work in the presence of a dielectric fluid. Through the eroding action of short duration electric arcs, or sparks, generated between the tool (electrode) and the work, material is being removed as the tool advances into the work. The activity of the electric charges is surrounded by a dielectric fluid flow which washes away loose particles and provides cooling, thus maintaining spark control. LMSC has several of this type of machine available for this program. No development in this area is required.

2.1.4 Chemical Etching

In LMSC there are two methods for etching beryllium by chemical action. One is a straight chemical method and the other uses an electrolyte which is imposed with an electrical potential. The former method is quite common and requires a series of chemical tanks. Cutting is entirely accomplished by chemical action at room temperature. The depth and rate of cut are controlled by immersion time for the former and by solution concentration for the latter. LMSC has complete chem-etching lines capable of handling structures 6 ft. wide by 15 ft. long. This capability is more than adequate for this program.

The latter method, referred to as Electrochemical Machining (ECM), utilizes electricity, chemistry, and basic mechanical components to remove material from a work piece in accordance with the precepts of Faraday's law. ECM removes metal from a work-piece by electrolytic action. The rate of metal removal is

determined by the area between the tool (cathode) and the work-piece and the rate at which the tool is fed against the stationary work-piece. The cathode tool never touches the work-piece so there is no wear, and no damage from heat of sparking. LMSC has several of this type of machines including one with 20,000 amp capacity supported by a 200,000 gallons source of electrolyte. No development in this area is required.

2.1.5 Surface Cleaning and Preparation

In addition to the above described chemical etching facilities which are used also for preparing beryllium surfaces, LMSC has several vapor degreasers, vapor blast chambers, chemical cleaning tanks, etc., to handle any cleaning and surface preparation requirements for this program. No development is required in this area.

2.1.6 Thermal Forming

As stated earlier, LMSC is currently hot-forming beryllium skin panels for the Agena vehicle and many other configurations fabricated from cross-rolled beryllium sheets. Our beryllium production area in Building 170 is equipped with many banks of electrical power supplies and controllers for any heating requirements. Both forced air and vacuum furnaces up to 1600°F temperatures are on hand. Recently, a 250 ton capacity hydraulic press equipped with a 57" x 72" heat box has been installed to provide additional thermal forming capability.

The above facilities have produced hundreds of medium size parts in production. Long and narrow configurations in excess of 3 ft. are not within our experience. Although LMSC does not anticipate insurmountable problems in forming the proposed channel stiffeners, however, the exact method in providing accurate temperature control over the entire forming cycle needs to be developed. This is one of the areas that requires development.

2.1.7 Riveting

Attaching beryllium skins to metallic framework with rivets is a routine production activity at LMSC. Several different types of rivet, such as monel, titanium, Lockalloy, etc., had been used successfully. No development in this area is required.

2.1.8 Mechanical Joining

Several types of mechanical fasteners have been successfully used by LMSC for joining beryllium to either beryllium or other metals. The mechanics of placing holes in a sheet and installing the fasteners at assembly is well within LMSC's capabilities and requires no development.

The area that needs development is related to design requirements. To be cost-effective, the broadest possible tolerances in terms of hole sizes and locations must be allowed for beryllium structures where a large cluster of fasteners is used to distribute a concentrated load. It is costly to match drill all components for an assembly in order to forestall any unknown in the behavior of the joint. If the utilization of beryllium in space structures is to be advanced further, a better understanding of such designs is needed. Development to determine fit-tolerance versus joint capacity is required.

2.1.9 Fluxless Brazing

LMSC has brazed beryllium using several different braze alloys. The majority of the work has been with aluminum and zinc using torch or forced air furnace as the heat source. Occasionally, cracked beryllium panels are brazed-repaired with zinc in accordance with the requirements of an established internal standard procedure.

Currently, LMSC is applying a fluxless brazing technique to attach formed beryllium stiffeners to a thin panel under NASA Contract NAS-8-27074. This process can be quite effective for manufacturing non-extruded tubular sectional members as those required in a large truss beam. Development in this area is planned.

3. PROCESS DEVELOPMENT PLAN

The three prime areas to undergo further development are:

1. Hot forming of long channels.
2. Permissible fit and tolerance for multiple fastener patterns.
3. Fluxless brazing of tubular shapes.

Development will be directed primarily to extending existing capabilities in these areas to cope with larger and more complex structures. Any new technique so developed will be applicable also to other structures of the space shuttle system. The development approaches and the results desired are described in the following paragraphs.

3.1 Thermal Forming

Although cross-rolled beryllium sheets exhibit a large percentage of elongation between 400-600°F, damage-free forming of it cannot be accomplished at this temperature range. LMSC's experience has proven that parts can only be properly formed within a temperature range from 1350°F to 1420°F. Within this narrow range one must find the optimum forming temperature most suited for the size, configuration and tooling design. Beryllium, with its high thermal conductivity (almost that of cast aluminum) as well as high specific heat (about twice that of aluminum alloys), is extremely sensitive to the heating environment during the forming operations. Therefore, the tooling design and forming procedure for each configuration must take these characteristics into consideration. Under proper conditions, cross-rolled beryllium sheets can be formed by several methods including draw forming. The integrity of a formed shape not only is dependent on how it is being formed, but also how accurately the post forming temperatures are being controlled. Superior properties can be developed by rapid quenching at forming temperature. The difficulty is to control temperature uniformity during cooling. Common practice for other heat-treatable alloys such as water quenching will be too severe for beryllium and too difficult to control. The cost of a single reject will more than offset production time saved. Therefore rapid air cooling is the most practical method. For long and narrow channels, an effective method must be found to passively control temperature distribution over the work-piece during forming and cooling to assure that the end product will be straight, flat and stress free. The development task is to establish a firm method of passive cooling. To accomplish this, the following experiments will be conducted.

A series of 4 channels, identical in size and length to that to be used for the small compression panel (SK 100125), will be formed under various temperature ranges. The thinner section (.090) is expected to be more sensitive to temperature variation than the thicker (.125) section. Therefore, it is selected as a more representative test bed.

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A set of mated forming die (Figure 1) will be used to form the channels. This die will be placed in a heated enclosure. The upper and lower portion of this enclosure are directly mounted respectively to the upper and lower platten of a 4 post 250 ton hydraulic press. Banks of electrical heating elements are contained in the opposing internal faces of the enclosure and are thermostatically controlled. Figure 2 shows the schematic arrangement. A flat blank placed in the open die is brought to the proper forming temperature within the enclosure. The hydraulic press will cause the die to close and the blank is formed.

Subsequent to forming, the part will be quickly transferred into a cooling box surrounded by loose high temperature insulation material such as "vermiculite" or equivalent, until it is uniformly cooled to a safe handling temperature.

Thermocouples will be attached to the channel along its length and coupled to channel recorders to retain temperature histories at designated points over the entire forming and cooling cycle. Once cooled, each channel will be given a dimensional check and correlated with die dimension and forming temperatures. Any deviation in straightness and flatness over an acceptable limit to be determined will be considered distorted. The most distorted of the first 4 runs will be reheated and reformed using the temperatures at which the best channel of the 4 was made. By strategic manipulation of the heating element output to attain the desired temperature distribution in the die and arrangment of packing material during cooling, adequate temperature control can be made. Through iteration of these steps a repeatable forming procedure for the selected channel design will be developed. Production channels will then be formed in accordance with this procedure. Table 1 depicts the type of data to be acquired.
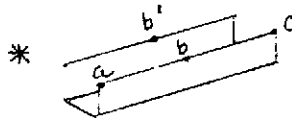
FORMING CYCLE NO.	CHANNEL NO.	TEMP AT FORMING (°F) *				MAX. TEMP. DIFF. (°F) DURING COOLING CYCLE			
		a	b	c	b'	a-b	b-c	b-b'	a-c
1	A								
2	B								
3	C								
4	D								
5	B2								
6									
7									
8									

TABLE I – THERMAL FORMING DEVELOPMENT RECORD

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BOLSTER PLATE

5 t (TYP.)

BERYLLIUM BLANK

LOCATOR
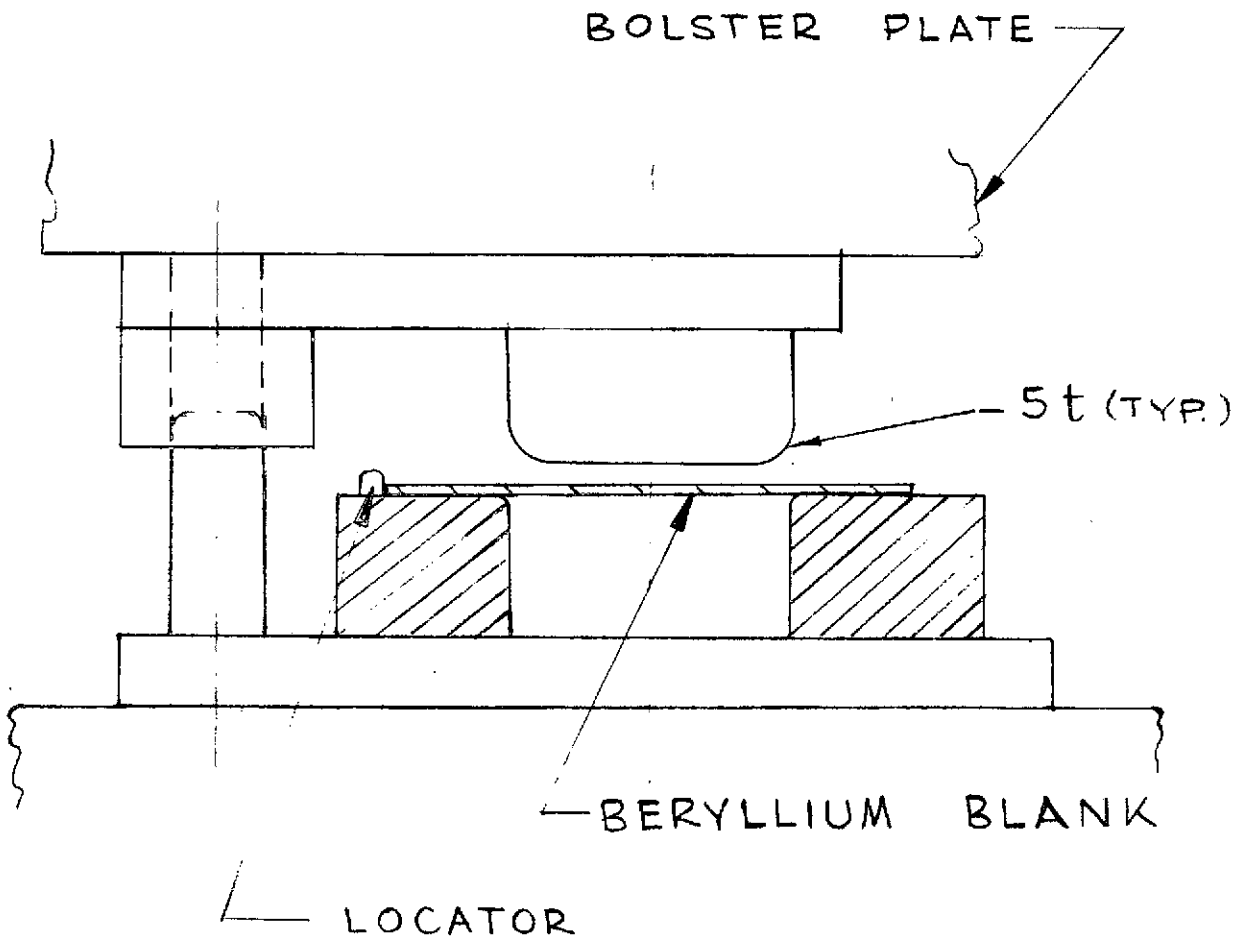
FIG. 1 - CHANNEL FORMING DIE
CONCEPT
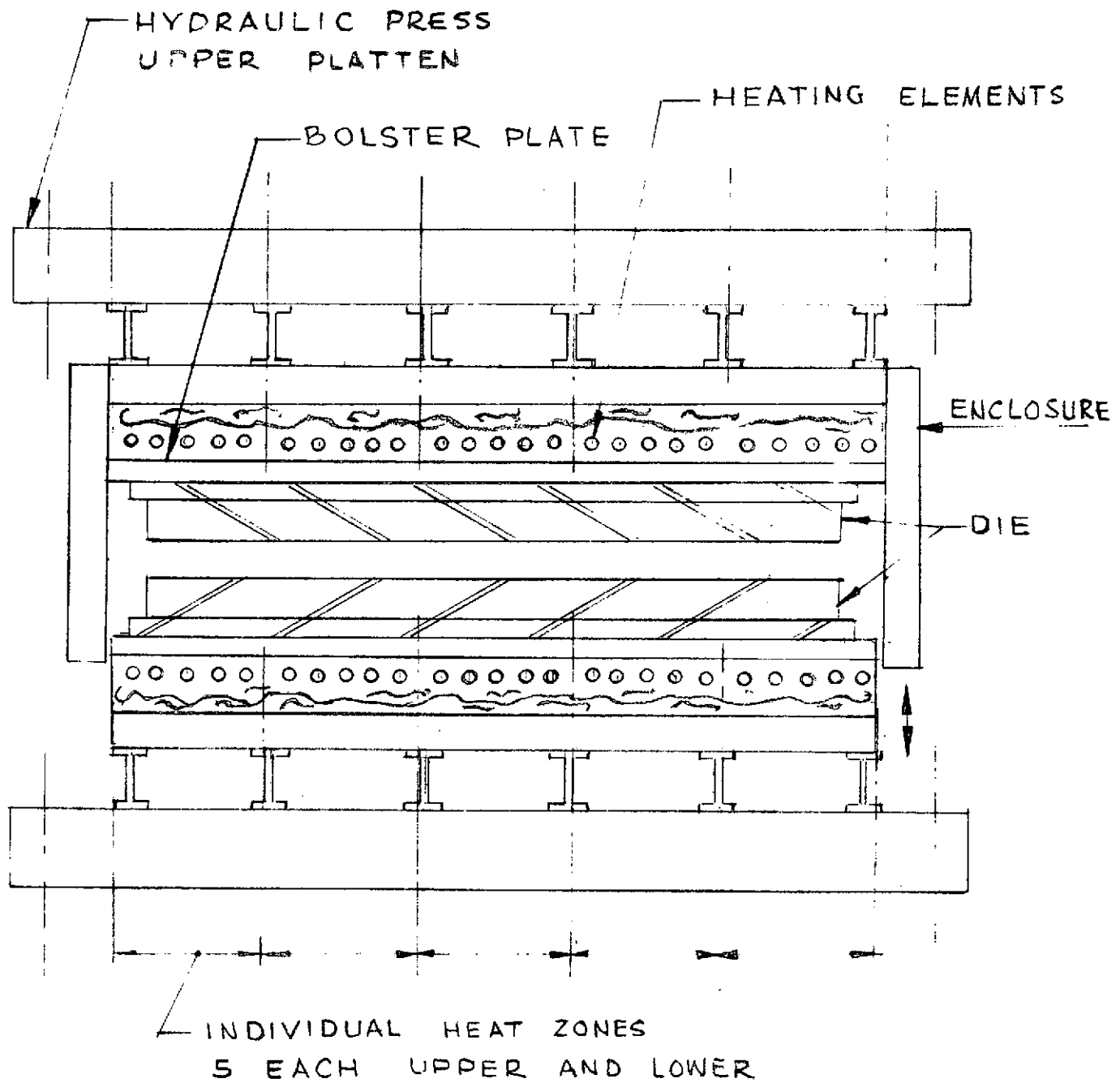
FIG. 2 — THERMAL FORMING EQUIPMENT ARRANGEMENT

3.2   Fit Tolerance Study

In a multiple fastener joint made up of isotropic materials such as aluminum
or steel, the applied concentrated load is proportionately distributed to the
individual fasteners according to the location of the Centroid of the fasteners.
Each fastener is assumed to be effective, irrespective of tolerance effects.
Although a few fasteners may be the only ones to resist the initial loading
(tighter fits), local deformation through bearing yield will cause redistri-
bution of the load to other fasteners, and ultimately all fasteners will come
into play, validating the assumed centroid location. With a beryllium joint
this may not be so. Cross-rolled beryllium sheet, being anistropic and having
short transient from bearing yield to tensile ultimate, its ability to allow
load redistribution over the entire fastener pattern needs to be determined,
so that realistic tolerances for fabrication and assembly may be allowed. With-
out a realistic guideline, the designer cannot help but impose very stringent
tolerances on hole size and location which can increase a structure's cost.
Therefore development needs to be conducted to determine the limits under
which a mechanical fastener joint can be treated in the same manner as other
isotropic material.

A series of test specimen as shown in Figure 3 will be destructively tested
to correlate individual fastener fit tolerance with joint capacity. By com-
bining low cost material such as 17-7PH stainless steel which has a high
bearing allowable, with beryllium, the cost of each test specimen will be
greatly reduced without jeopardizing the accuracy of test data.

A master drill template will be fabricated (drilled) together with the stain-
less steel yoke. This template having the exact hole size and location as
that in the steel yoke, will be used to control drilling of holes in all of
the beryllium test specimens. Holes in the beryllium pieces will be reamed
or etched to yield diameters as close as possible to that of the fasteners.
Exact measurements of these dimensions in each beryllium test piece will then
be selectively enlarged to 1, 2, and 3 thousands of an inch oversize either
by chem-milling or mechanical reaming. Each beryllium specimen will be assembled
to the steel yoke using calibrated (dia) high strength fasteners at pre-deter-
mined torque values. Each piece is tested to failure under the exact condition.
Data thus generated are expected to show how the fit tolerances affect load
distribution over the entire joint.

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STAINLESS STEEL YOKE

P

BOLT PATTERN

45°

20°

15°

30°

BERYLLIUM SPECIMEN

ALUM. DOUBLER BONDED TO BERYLLIUM

P
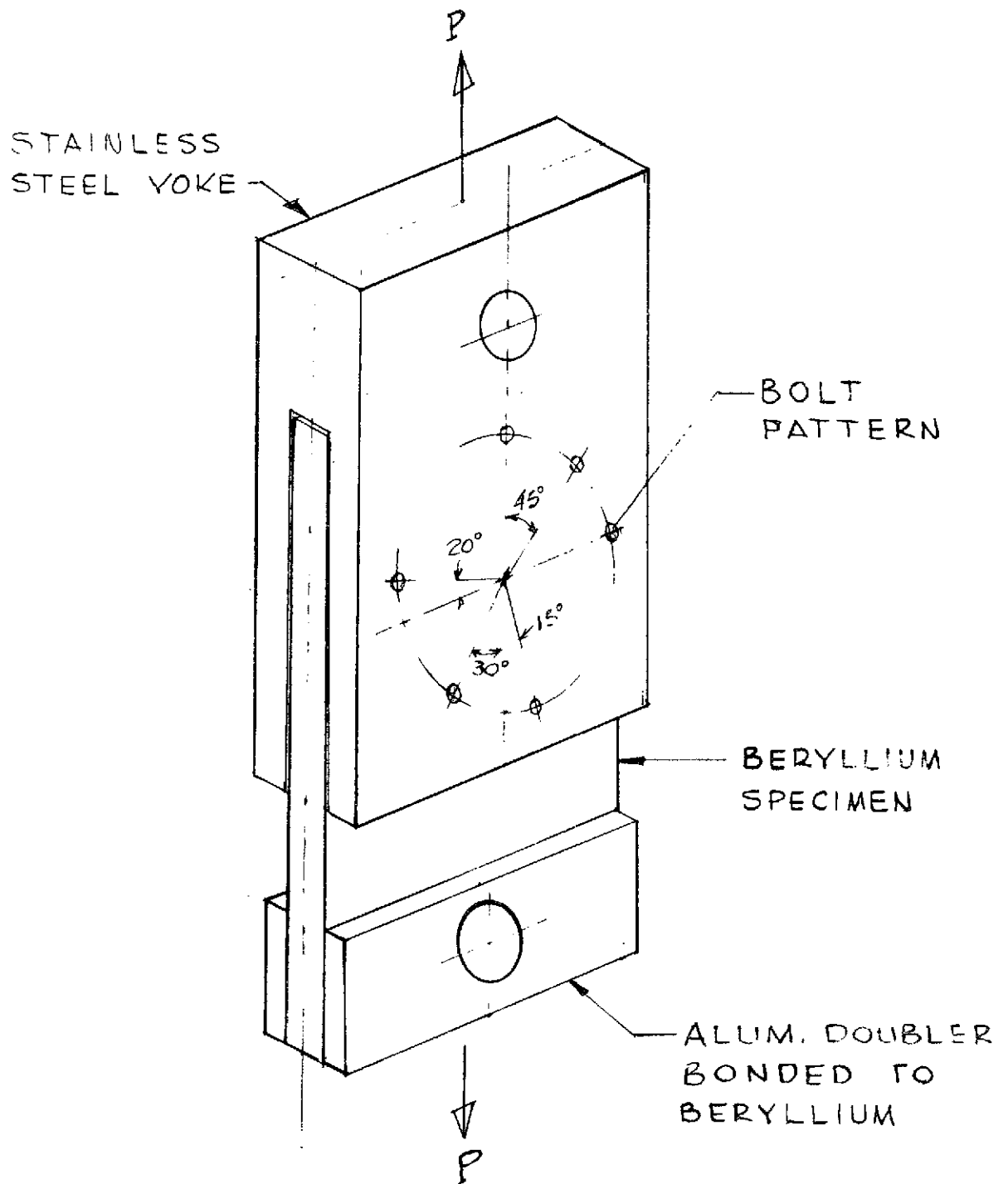
FIG. 3   FIT-TOLERANCE STUDY TEST SPECIMEN CONCEPT

Table II illustrates the type of data to be generated.

Be Spec.	Hole Clearance(in)			ULT Load (Pound)	Loading Rate (in/min)	Failure Mode
	a	b	c			
1	.001	0	0			
2	.001	.001	0			
3	.001	.001	.001			
4	.002	.001	0			
5	.002		0			
6	.002	.002	.002			
7	.003	0	0			
8	.003	.003	0			
9	.003	.003	.003			
10	.004	0	0			

TABLE II – FIT-TOLERANCE DEVELOPMENT RECORD

3.3   Fluxless Brazing Development

Tubular beryllium structural members having a cross-section area larger than available extrusion capability, must be built up with fabricated or smaller extruded elements. These elements can either be assembled with mechanical fasteners or brazing. Adhesive bonding and soldering offer only low strengths. Mechanical joining encounters many fabrication problems such as hole size, true centers, accessability, etc. Furthermore, beryllium sheets require a 5-6t bend radius. For heavy gage material such as .125", to develop any usable flat surface in an angle for joining, each leg must be wider than 1.625" for a .25 dia fastener using a 6 t bend radius.

On the other hand fluxless brazing offers certain advantages. As the material gage increases, the thickness itself may provide sufficient brazing area. Holes can be introduced to each mounting surface prior to brazing. For example, a large rectangular box section can be built up with four flat pieces without the aid of corner angles as shown below.

—BRAZE (TYP)

N.A.

$t < .10$
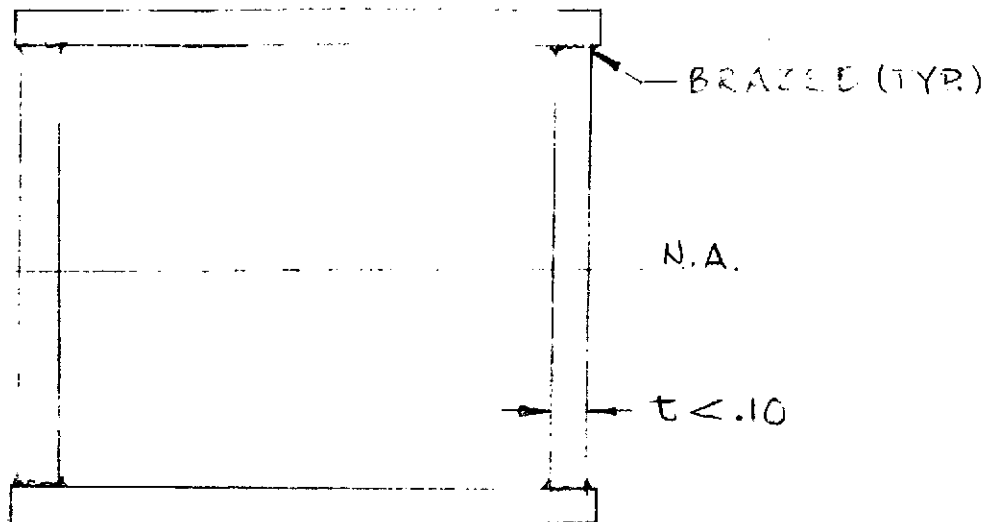
Therefore it is planned that investigation will be conducted to assemble rectangular tubular sections by fluxless brazing.

About 4 members, 20" long each, will be assembled with the fluxless brazing method using BAg18 braze alloy (60 Ag, 30 Cu, 10 Sn) as the first candidate. Aluminum and zinc based brazing alloys will also be considered. This braze alloy is being used to attach beryllium hat sections to a thin (.015") panels for a NASA Contract NAS 8-27074. Since the prime objective is to evaluate the feasibility of assembling tubular section by brazing rather than the brazing process itself, it is felt that the most effective approach is to utilize an available brazing process and material. This will avoid introduction of other variables into the development.

In addition to the requirement of structurally joining the elements into a composite tubular section, there is also a requirement to provide a means to attach reinforcing gussets or tabs. Brazing such onto the assembly could be accomplished with a lower melting temperature alloy. This introduces the requirement of large furnaces as well as being limited to a lower strength brazing alloy. A means to allow attachment of such gussets by mechanical fasteners is more desirable. To alleviate assembly problems, captured female receptacles for fasteners must be provided for. Development will be directed to answer these two needs.

Stainless steel platenuts or equivalent will be brazed on simultaneously during the same brazing cycles when all elements are assembled. These nuts will be held in position with retainers made of material which is not compatible to the braze alloy. In the early part of the development, selection of this material will be tested to insure that it will not be brazed by this alloy. Material such as ceramic or carbon will be considered. The general set-up for brazing is illustrated in Figure 4.

Prior to final assembly of the four (4) structural members, the method to attach stainless steel nuts to a flat surface will be checked out by scale assemblies. About 6 nuts will be brazed onto a plate with pre-drill holes. These nuts will be held in position by special retainers and brazed with the same process to be used for final assembly. Each nut will be subjected to a pre-determined torque value, 150% of the allowable installation torque for that size of fastener. All test values will be recorded. Any failure will be noted and the brazed area examined to determine cause.

Once the method has been proven workable, based on torque test values, it is then incorporated into the brazing operation of the four (4) structural members. In addition to a dimensional check, photo micrographs will be taken on an end cut. One completed member will be subjected to a simple shear loading test.

20

3

3.2

BRAZED

P

P
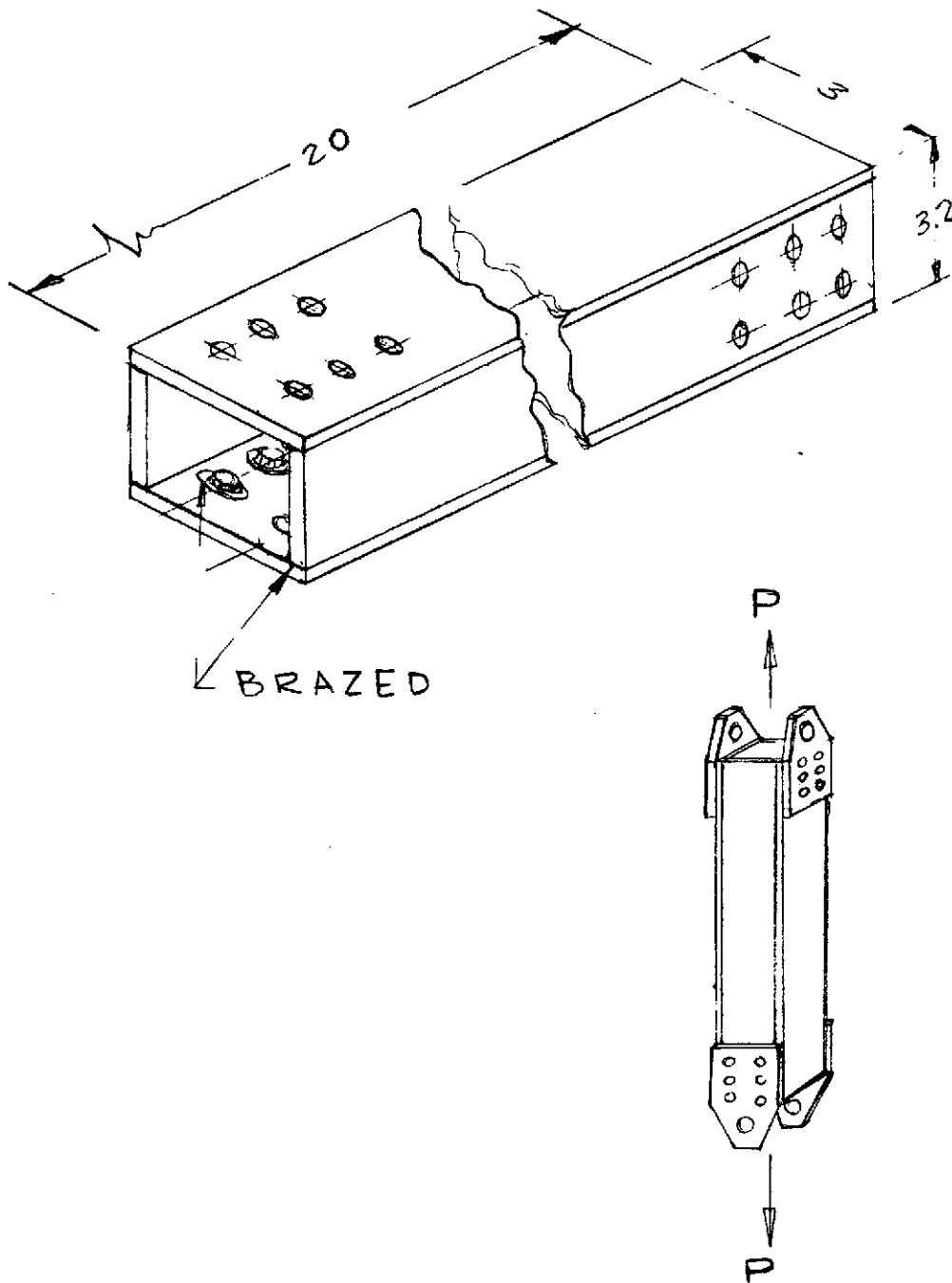
FIG 4   BRAZING   DEVELOPMENT
TEST   SPECIMEN   CONCEPT

4. <u>EVALUATION AND APPLICATION OF RESULTS</u>

The prime purpose for conducting the above described developments is to establish process techniques and procedures for effective fabrication of large beryllium structures, specifically those designs selected for this program. Therefore, the development outputs must be measured on their applicabilities to manufacture the candidate designs as well as potential designs for space shuttle structures. The ultimate result would be a set of workable process specifications with which a piece of large beryllium structure can be repeatably fabricated by a qualified beryllium production shop. It is on this basis that the following evaluation format is recommended.

4.1 Thermal Forming

It is recommended that the results and conclusions derived from thermal forming development be evaluated in the following format:

	EXCEEDED REQMT.	ADEQUATE FOR PROGRAM	IMPROVEMENT NEEDED
1. DESIGN OF DEVELOPMENT TASKS			
2. DOCUMENTATION			
3. MEETING THE OBJECTIVE			
4. DIE DESIGN			
5. EQUIPMENT SET-UP			
6. FORMING METHOD			
7. TEST METHOD			
8. DATA ACQUISITION & THEIR APPLICATION			
9. APPLICATION FOR CURRENT DESIGN			
10. APPLICATION FOR OTHER SPACE SHUTTLE STRUCTURES			
COMMENTS:			

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4.2   Fit Tolerance Study

The results of development conducted are to be evaluated per the following:

	EXCEEDED REQMT.	ADEQUATE FOR PROGRAM	IMPROVEMENT NEEDED
1. DESIGN OF DEVELOPMENT TASKS			
2. DOCUMENTATION			
3. MEETING OBJECTIVE			
4. TEST SPECIMEN DESIGN			
5. TEST SPECIMEN FABRICATION			
6. TEST METHOD			
7. DATA ACQUISITION AND THEIR APPLICATION			
8. APPLICATION FOR CURRENT DESIGNS			
9. APPLICATION FOR OTHER SPACE SHUTTLE STRUCTURES			
COMMENTS:			

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4.3   Fluxless Brazing

The following format is recommended for evaluation the development in this area:

	EXCEEDED REQMT	ADEQUATE FOR PROGRAM	IMPROVEMENT NEEDED
1. DESIGN OF DEVELOPMENT TASKS			
2. DOCUMENTATION			
3. MEETING OBJECTIVE			
4. BRAZING FIXTURE DESIGNS			
5. EQUIPMENT SETUP			
6. BRAZING METHOD			
7. TEST METHOD			
8. DATA ACQUISITION AND THEIR APPLICATION			
9. APPLICATION FOR CURRENT DESIGN			
10. APPLICATION FOR OTHER SPACE SHUTTLE STRUCTURES			
COMMENTS:			

5. SUMMARY REPORT AND RECOMMENDATIONS
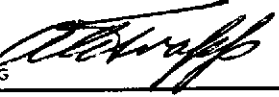
Upon the completion of all the development tasks, data acquired through fabrication of test specimens and their testing will be reviewed and analyzed. These data will be evaluated to determine their applicability to: 1) manufacture the deliverable test structures, and 2) other potential structures for the space shuttle system. Process procedures for forming the long channels and fit tolerances recommended for design of fastener clusters will also be documented. Additionally, a summary report will be prepared and submitted to customer. Included in this report will be specific recommendations on immediate applications as well as follow-on actions.

Appendix P

EM B1-M4-1B

FABRICATION ESTIMATES FOR
BERYLLIUM PANELS

ENGINEERING MEMORANDUM

TITLE:	EM NO: B1-M4-1B
FABRICATION ESTIMATES FOR BERYLLIUM PANELS	REF:
	DATE: 8/8/72
AUTHORS: J. S. Denend	APPROVAL: ENGINEERING / SYSTEM ENGRG

PROBLEM STATEMENT

Develop or accumulate progressive fabrication estimates to provide data for cost trends for required beryllium panels at the key points of conceptual design, design release and fabrication. These data will provide the basis for cost projections for the truss and shear beams, considering the methods and techniques to be employed in a production type atmosphere.

RESULTS

During the period May-June 1971, estimates based on conceptual drawings and sketches were prepared for the tasks involved with the fabrication and assembly of two (2) configurations of compression panels. The attached tabulation presents: a) results of estimates to the conceptual sketches and a format for reporting updated estimate results, b) the results of estimates made in Jan. '72 of released drawings and c) actual budgets used in fabrication of the delivered panels.

DISCUSSION

On receipt of released detailed design the production fabrication and assembly tasks were reestimated to account for changes required by detailed analyses. In addition to the factors of parts, size and complexity, factors of profiling, forming, progressive processing, drilling, attaching and final finish were analyzed with respect to rate of production. Tooling requirements were determined on a basis of requirements for flatness, forming environments and tolerances, special handling requirements and rates of production. Notes have been added to the tables to give an insight into the comparison of estimates and final figures. The experience revealed that the techniques of estimating were reasonably accurate with respect to fabrication but that tooling requirements were overestimated for the limited production in this program. Confidence has been provided in the estimation of time required for the fabrication of the truss and shear beam included in the cost evaluation EM B1-M2-11.

ITEM	Preliminary Design	Released Detailed Design	Actuals
1.1 Compression Panel (29 x 80)	SKS 100125	SKJ 201002	SKC 201002
Detail 3 Channels (9 Req'd.)	132 Hrs	180	
Detail 1 Panel	37	75	
Detail 7 End Plates	18	35	
Titanium Pcs.	20	20	
Detail 5 Doublers	22	40	572 Hrs ①
Miscellaneous Details	72	72	
Assembly	50	60	
TOTAL	351 Hrs	482 Hrs	
1.2 Tooling			
Form Die - Be Parts	375 Hrs	375	——— ②
Stress Relieve Tool	150	150	——— ③
Router Template - Ti Parts	20	20	80 Hrs ④
Drill Template	36	36	
Fabrication Aids	48	48	——— ⑤
TOTAL TOOLING HRS.	629 Hrs	629 Hrs	

DISCUSSION

Rev. A - Increases in detail estimates - SKJ 201002 are the result of increased parts complexity (end cuts), increased attachment, and added countersink requirements.

Rev. B - (1) Hours quoted are actuals of 702 less 130 hours for rework of unacceptable parts which included the basic panel, two doublers and one stiffener.
   (2) Includes forming die for all channels. Total hours used = 364 hours which included die rework.
   (3) Tool not required.
   (4) Because of commonality of tooling, charges prorated as shown.
   (5) Fabrication aid charges not identified.

ITEM	Preliminary Design	Released Detailed Design	Actuals
2.1 Compression Panel (48 x 72)	SKS 100130	SKC 201001	SKC 201001
Fab Be Details – 1 thru –13	616 Hrs	495 Hrs	} ———— ①
Fab Ti Details & 301,303,305&306 Assem.	143	342	
Chem Mill – Drill & Etch & Countersink	525	400	} 1221 Hrs
Miscellaneous Details	40	40	
Assembly	140	196	}
TOTAL PANEL	1,464 Hrs	1,473 Hrs	
2.2 Tooling			
Ti Form Die	120	120	} ———— ②
Ti Sizing Die	60	60	———— ③
Drill Templates (Approx. 5)	40	180	} 124 Hrs
Assembly Fixture	80	80	———— ④
Misc. Fab Aids	24	24	———— ⑤
TOTAL	324 Hrs	464 Hrs ⑥	}

DISCUSSION

Rev. A - SKC 201001 total estimated hours vary nominally. Differences in detail result from more detailed depiction of Be and Ti requirements, increased attachment, and the added requirement for countersink for rivet heads. The increase in tooling results from greater visibility of template need for detail parts drilling.

Rev. B - (1) Change from welded construction to machined billet reduced effort required.
(2) Die not required.
(3) Die not required.
(4) Fixture not required.
(5) Fab aids not identified.
(6) With noted items not required total tooling quote reduces to 204. Reduction of templates to 2 would further reduce total to approximately 90 hours.

Appendix Q

EM B1-M4-2A

BERYLLIUM SHEET
UTILIZATION LAYOUTS

ENGINEERING MEMORANDUM

TITLE: BERYLLIUM SHEET UTILIZATION LAYOUTS	EM NO: B1—M4—2A
	REF: REV A, 7-21-72
	DATE: 15 December 1971
AUTHORS: G. S. Fuchigami/S. Lee	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Provide assurance that the beryllium sheet stock will be put to maximum usage for
the parts to be manufactured, the back-up parts, and the test specimens.

RESULT

Sheet cutting diagrams were made up to recommend certain cutting procedures
for the maximum utilization of each sheet.

DISCUSSION

Indiscriminate cutting of the sheet stock to make the required parts will lead to
excessive scrappage of this expensive material. In order to minimize this
scrappage, provide the maximum back-up material for extra parts, and provide
enough test specimen material in its proper orientation, a utilization layout
was made as follows for each sheet of the total of fifteen sheets ordered.

These patterns have been coordinated with members of those organizations having
responsibility for design, material test and manufacturing to ensure the
consideration of all material requirements.

REV A, 7-21-72

Producer's identification numbers added for each sheet. (Pressing and

Part Numbers)

PROPOSED SHEET USAGE

$(.124 \, ^{+.009}_{-.009}$ Sheets)

	PRESSING NO.	KBI S/N
	379P	H-1514

91"

35"

(SKJ 201002 Panel)
29" X 80"

385 in²

① 5½ × 78¾" Stiffener

	PRESSING NO.	KBI S/N
	379P	H-1509

② 5½" × 78¾" Stiffener
③ ''   ''
④ ''   ''
⑤ ''   ''
⑥ ''   ''
⑦ ''   ''

420 in²

	PRESSING NO.	KBI S/N
	379P	H-1510

⑧ 5½" × 78¾"   Stiffener
⑨ ''   ''

(SKJ 201004 Panel)
15¼" × 40" Ⓣ

② 5½" × 38¾" Stiffener Ⓣ
③ ''   '' Ⓣ
④ ''   '' Ⓣ

⑩ 5½" × 38¾" Stiffener Ⓣ
⑤ ''   '' Ⓣ

420 in²

Ⓣ = Sub-Panel Test Item

PROPOSED SHEET USAGE (Cont'd)

$$(.124 \, ^{+.009}_{-.009} \text{ Sheets})$$

	PRESSING NO.	KBI S/N
	379P	H-1511
	379P	H-1512

① 8⅛" x 29" Doubler   ② 8⅛" x 29" Doubler   ① ① 8⅛ x 15¼" Doubler   ② 8⅛ x 15¼" Doubler

(T)   "5½ x 38¾" Stiff. Back-up
15¼" x 40" Panel   2. "   "   " (T)
Back-up   150 in²
5½" x 78¾" Stiffener Back-up
2.   "   "   "

310 in²

29 x 80 Panel Back-up

5½" x 78¾" Stiffener Backup

385 in²

(T) = Sub-Panel Test Item

Q-3

EM NO: B1-M4-2Am 7-21-72
DATE: 15 December 1971

PROPOSED SHEET USAGE (Cont'd)

$(.140 \begin{smallmatrix} +.012 \\ -.010 \end{smallmatrix}$ Sheets)

	PRESSING NO.	KBI S/N

84"

①
SKC 201001 Panel
24" × 72"

360 in²

① 5½" × 71"   Stiffener

| 395P | H-1517 |

30"

---

② 5½" × 71" Stiffener
③   "   "
④   "   "
⑤   "   "
⑥   "   "

400 in²

| 432P | H-1532 |

1"

---

②
SKC 201001 Panel
24" × 72"

360 in²

⑦ 5½" × 71" Stiffener

| 432P | H-1535 |

---

⑧ 5½" × 71" Stiffener
10" × 48" Doubler   8" × 36" Doubler
8" × 66" Doubler
⑪ 5½" × 40½" Stiffener ⓣ   ⑫ 5½" × 40½" Stiffener ⓣ

200 in²

| 432P | H-1533 |

8" × 58" Doubler   8" × 26" Doubler ⓣ
10" × 35" Doubler ⓣ   8" × 34" Doubler ⓣ
○ 5½" × 71" Stiffener Back-up
⑤ 5½" × 71" Stiffener Back-up

270 in²

| 432P | H-1534 |

ⓣ = Sub-Panel Test Item   Q-4

PROPOSED SHEET USAGE (Cont'd)

(.140 $^{+.012}_{-.010}$ Sheet)

	PRESSING NO.	KBI S/N

84"

		432P	H-1536

30"

SKJ 201007 Panel 17½" x 42" (T) | SKJ 201007 Panel 17½" x 42" (T)

③ 5½" x 40½" Stiffener (T) | ⑤ 5½" x 40½" Stiffener (T)

④ " " (T) | ⑥ " " (T)

	395P	H-1516

8" x 35" Doubler (T) | ① 5½" x 40½" Stiffener Back-up (T)

② 5½" x 40½" Stiffener Back up (T) | ③ 5½" x 40½" Stiffener Back up (T)

8" x 58" Doubler Back up | 8" x 26" Doubler (T) Backup

⑤ 8" x 35" Doubler Backup | ⑥ 8" x 34" Doubler Backup

	395P	H-1518

SKC 201001 Panel Back-up 24" x 72"

③ 5½" x 71" Stiffener Back-up

	432P	H-1537

SKJ 201007 Panel (T) 17½" x 42" Backup. | 5" x 42" Truss Beam (T)
  | " " " (T)
  | 4" x 42" " " (T)
  | " " " (T)

5 x 42 Truss Beam Back-up (T) | (T) " " " Back-up
" " " " (T) | (T) " " " Back-up

	395P	H-1515

(T) = Sub-Panel Test Item   Q-5

Appendix R

EM B1-M4-3

PRELIMINARY PROCESS PLAN

ENGINEERING MEMORANDUM

TITLE:	EM NO: B1-M4-3
Preliminary Process Plan	REF:
	DATE: 6 January 1972
AUTHORS: S. H. Lee	APPROVAL:
	ENGINEERING
	SYSTEM ENGRG

PROBLEM STATEMENT

Develop a preliminary process plan which identifies the major fabrication and
assembly operations being planned for the construction of the full size compression
(uniform and concentrate loading) beryllium panels.

RESULTS

A typical process flow chart is depicted in Figure 1. Most of the major operations
as shown are typical LMSC in-house processes established for beryllium cross rolled
sheets. However, some operations will include certain refinements tailored specifically
to meet the more stringent dimensional tolerances required. For example, actively
controlled post forming cooling rates for the long "C" channels, match drilling of
components, constant driving force for rivet installation, etc.

DISCUSSION

Since both the design and fabrication of these compression panels invoke many
"firsts" in beryllium applications, both success and failure in every fabrication
step can be exceedingly meaningful for future design. Accurate traceability through
each step of the process flow in terms of material pedigree and process parameters
is essential to validate any analysis. Therefore, prime consideration has been
given to this requirement in the planning of the process flow.
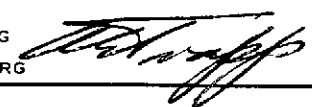
All sheet stocks ordered for this contract are individually identified and stored as
a separate group within the beryllium shop. Cutting patterns were developed for
each sheet to maximize material utilization. These patterns are mapped on the
sheet prior to cutting with the discrete sheet identity repeated on each individual
blank. These identities will be maintained all through the fabrication cycle.
Similarly, process parameters which deviate from prescribed values in terms of
temperature, time, etc., will also be recorded against the respective component
involved.

The major operations shown in the process flow chart are described herein as reference:

OPERATIONS   METHODS

● Cutting   a. Constant speed diamond abrasive wheel
                                    with pressure-fed coolant

                                b. Air motor-driven router bits

                                c. Milling machine with end mills

                                d. Electric-discharge-machining (EDM)

                                e. Chemical etching

        NOTE: Where more than one method is listed, the specific
               method being used is dependent on the size and
               geometry involved.

● Hole Drilling   a. "TORNETIC" air motor system with
                                    special carbolay drills

                                b. EDM

● Forming   a. Stainless steel die set backed up by
                                    self-heating ceramic bolster plattens.
                                    Each platten is equipped with multiple
                                    banks of heating elements to provide
                                    time temperature control desired

● Cleaning and Surface   a. Vapor degreasing
  Removal
                                b. Vapor honing

                                c. Chem-etching tank system

● Joining   a. Squeezed monel rivets

                                b. Fluxless brazing (for test components)

Appendix S

EM B1-M4-4

QUALITY PROGRAM PLAN

ENGINEERING MEMORANDUM

TITLE: QUALITY PROGRAM PLAN	EM NO: B1-M4-4
	REF:
	DATE: 5 January 1972
AUTHORS: D. E. Draeger/R. E. Lord	APPROVAL: ENGINEERING / SYSTEM ENGRG

PROBLEM STATEMENT

Describe the Quality Program in support of the development of material properties, processing techniques, design details, and fabrication of components from beryllium metal for the program "Evaluation of Beryllium for Space Shuttle Components".

Applicability

LMSC Basic Quality Control Specification (LMSC/579218) establishes the minimum quality control requirements for research and development programs.

Documentation

Drawing Control

Drawings, sketches, specifications, test procedures, and/or planning documents used to establish acceptance criteria shall be controlled as described herein.

Drawings, sketches, test procedures and other documents used as acceptance criteria, may be marked up (redlined) during the production cycle as authorized by the Program Manager or responsible engineer, but must be clear and legible with redlines signed and dated by the engineer making the change. When released documents are a requirement, acceptance will be withheld pending an evaluation of the compatibility between the released documents and the redlined documents used to produce the item. When released documents are not a requirement, the redlined documents must be maintained as part of the inspection record.

Drawing release or change programming may be accomplished by direct negotiation between representatives of Engineering, Manufacturing, Procurement and Product Assurance as directed by the Program Manager or his delegate. All changes will be brought to the attention of the PA Program Representative and/or cognizant Quality Engineer.

Records

Records such as Shop Orders, Operations Orders and Log Books will be maintained and identified for each unit to incorporate all pertinent data which will serve as a history of the unit. These records will contain as a minimum the following documentation:

(1) The date of Inspection/Test, test data and pertinent test conditions.

(2) All discrepancies which occur throughout the Program.

(3) A record of significant events affecting program quality so that at completion a summary of the program can be made.

Inspection discrepancies may be reworked to conform to requirements and will be recorded on the reverse side (back) of shop orders or similar test/fabrication documents.

Quality Engineering

Prepare quality criteria based upon LMSC quality standards and engineering specifications to control the quality of procured items: Review all procurement request documents (including sub-contracts) and add pertinent quality data; prepare receiving inspection instructions, receiving acceptance test procedures, and source verification/acceptance instructions as required.

Review shop work authorizing documents (SWADs) for inclusion of inspect points which identify pertinent characteristics of acceptance and insert or reference inspection instructions on the SWADs.

Provide Quality Engineering liaison support to the program for resolution of quality problems, and to the customer for point of contact for customer participation.

Data furnished with the purchase of materials will be reviewed to determine the suitability of the density, elongation, ultimate strength characteristics and chemical composition of the materials. Instructions for verification of

the vendor's data, including penetrant and radiographic inspection results and evidence of pickling will be prepared as required.

Traceability

Each panel will be permanently identified by etching and dyeing upon receipt. Records for each panel will be maintained to include vendor data (including lot numbers and date), receiving inspection data and all processing history of each panel.

Inspection and Test

a.   Receiving Inspection

All procured materials will be inspected upon receipt for thickness variation, flatness, quantity, evidence of surface porosity, identification and damage. Additionally, characteristics which require verification of the vendors data will be tested or inspected in accordance with the appropriate inspection instructions or acceptance test procedures.

b.   In Process Inspection (if required)

The fabrication will be inspected for compliance to drawing/sketch and surface damage, in accordance with the instructions prepared by Quality Engineering and referenced or inserted on the Shop Work Authorizing Document (SWAD). Identify date and initial is required to signify conformance or nonconformance.

c.   Final Inspection

The final inspection for compliance to drawing/sketch and etching requirements in accordance with the instructions prepared by Quality Engineering, and identified, initialed, and dated to indicate conformance or nonconformance.

d. Shipping Inspection

Inspection of items prior to shipment will be accomplished to assure that all pertinent documentation is in order, and that packaging has been accomplished according to applicable packaging data sheet specifications and/or customer requirements.

Test Equipment Control

Inspection and test equipment will be calibrated as frequently as necessary to assure accuracy. Inspection will verify that all measuring and test equipment have current calibration status prior to the start of any activity requiring the use of calibrated equipment.

Nonconforming Material

Product Assurance will maintain a quality system for identification, segregation, disposition and accountability of nonconforming materials or products. Review and disposition of nonconforming material will be performed by one Program Engineer and the Program PA representative.

Initiation of discrepancy and/or failure documentation will be accomplished by inspection. Notification of significant noncompliance occurrences will be forwarded to the cognizant Quality Engineer and/or the PA Program Representative.

Discrepancies which affect the surface conditions will be documented on a nonconformance report and submitted to the applicable Program Engineer and PA Engineer.

The Product Assurance Program Representative and/or cognizant Quality Engineer will support the program to the extent necessary to ensure the following:

a. Timely notification of cognizant Program Office of failures and discrepancies.

b.   Immediate disposition of discrepancies.

c.   Implementation of corrective action as required by the contract,
the Product Assurance Manager, or the Program Manager.

d.   Product quality for the items produced is documented.

Appendix T

EM B1-M5-1

EVALUATION OF SUBPANEL TESTING

ENGINEERING MEMORANDUM

TITLE: EVALUATION OF SUBPANEL TESTING	EM NO: B1-M5-1
	REF:
	DATE: 29 June 1972
AUTHORS: G.S. Fuchigami SSF	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

Evaluate the test data obtained from the subpanel tests conducted at LMSC.

RESULTS

This EM documents the test evaluation conducted for the testing of the Uniform Load Subpanel, SKJ 201004, and the Concentrated Load Subpanel, SKJ 201007.

DISCUSSION

Testing of subscale components of compression panels at LMSC is a contractual requirement. The detailed procedures followed in the testing of these panels is documented in EM B1-M2-6A (Ref. 1). The tests of the Uniform Load Subpanel, SKJ 201004, were successfully completed on 4/20/72, with panel failure occurring at approximately 200% of design limit load at 600° F temperatures. The tests of the Concentrated Load Subpanel, SKJ 201007, were successfully completed on 5/19/72, with panel failure occurring at approximately 151% of design limit load at 600° F temperature. Ultimate load is contractually specified as 140% design limit load for both panels. Each of the tests are evaluated in detail in this EM, together with predictions on the performance of the panels delivered to NASA/MSFC. Successful completion of these tests permitted the fabrication of the full scale deliverable panels as designed, with every confidence in their structural capabilities.

OBJECTIVES

Uniform Load Subpanel Test

- Verify analysis
- Verify end attachment (rivet) capability
- Verify transition from end fitting to skin-stringer panel
- Verify freedom from local effects that might precipitate failure
- Verify strength capability of panel and material
- Verify attachment of skin to stringers

Concentrated Load Subpanel Test

- Verify analysis
- Verify load distribution from concentrated load fitting to panel
- Verify uniform takeout end attachment capability
- Verify transition from uniform takeout fitting to skin-stringer panel
- Verify freedom from local effects that might precipitate failure

TEST EVALUATION OF UNIFORM LOAD SUBPANEL, SKJ 201004

The test configuration shown in Fig. 1 was subjected to a series of room temper-
ature and elevated temperature tests per the procedures of EM B1-M2-6A (Ref. 1)
starting 4/17/72 and concluding 4/20/72. The tests were conducted in the Struc-
tural Test Facilities of LMSC, Building 102. Figure 2 depicts the test set up and
the load and temperature requirements. Figure 3 shows the time-phased loading
followed in the testing. A deviation was made from this loading procedure in the
final test where a longer soak time at temperature was used. The following tests
were conducted in the sequence shown:

1. Room temperature test to 50 percent limit load.

2. Room temperature test to 100 percent limit load.

3. Elevated temperature test to 50 percent limit load.

4. Elevated temperature test to 100 percent limit load.

5. Elevated temperature test to 140 percent limit load, hold for ten seconds,
    and continue loading to failure.

The mechanical properties of the panel assembly used in this evaluation are the
verified values from LMSC testing where available. Panel and stiffeners are
from KBI Pressing #379P, Heat #H-1510. LMSC tested values are as follows:

		R. T.	600° F	(Ref. LMSC Tests)
F_{tu}	=	75.4 KSI	46.0 KSI	
F_{ty}	=	60.9 KSI	45.4 KSI	
F_{cy}	=	62.9 KSI	44.1 KSI	
e	=	21.5% in 1"	43.0 % in 1"	
*E	=	42.5×10^6 psi	37.0×10^6 psi	

Panel Thickness	=	.126 in.	
Stiffener Thickness	=	.116 - .122 in.	Ref. "as-built"
Doubler Thickness	=	.117 & .124 in.	measurements

*These are design values from EM B1-M2-1 (Ref. 2)

The 50% and 100% limit load tests at ambient temperatures were uneventful. Back-to-back strain gage data (Table I) in the middle of the panel showed minimal bending and good load distribution, while the gages located closer to the end fittings (gages 1 thru 6 and 17 thru 22) indicated that discontinuities existed in these areas as expected. The stresses measured by these gages compare favorably with the stresses predicted by STAGS analyses (Ref. 4) as shown on Table II. The following tolerances are to be considered with respect to the strain gage data:

Strain gage tolerances $\cong \pm 50$ μ-in $\cong \pm 2$ KSI

Strain gage readings $\cong \pm 10$ μ-in $\cong \pm .4$ KSI

The 50% and 100% limit load tests at 600°F were concluded with no problems or potential problems indicated in the data read-out. However, it was decided to soak the test specimen for approximately 10 minutes at 600°F prior to application of the load in order to get better distribution of temperature. This procedure was followed in the final test. After temperature stabilization for 10 minutes, 100% limit load was applied (78,300 lbs), held for 5 seconds, then 140 limit load was applied (110,000 lbs), held for 10 seconds, then the loading was continued until failure of the panel occurred at approximately 200% limit load (163,000 lbs). The data shows that gages 3, 5, 17, 19, and 21 indicated strains above the compressive yield stress at 140% limit load (Table I). Just prior to collapse of the panel, 17 of the 19 gages were reading strains in the plastic range of the material, indicating that extensive redistribution of loading in the panel had occurred.

Review of the STAGS analysis (Ref. 4) for the full size (deliverable) uniform load panel show that approximately 21% higher stresses are predicted for the same critical areas as compared to this test panel. These higher stresses are primarily due to the lack of edge restraint effects which occur in the smaller size panel. The STAGS analysis also shows that buckling is more critical in the larger (deliverable) panel; however, the failure mode is still the material failure mode (F_{cy}) rather than instability. Therefore, it is estimated that the uniform load panel to be tested at MSFC has the capability of reaching 170% of design limit load with similar strain redistribution.

SKJ 201004 TESTS - UNIFORM LOAD SUBPANEL
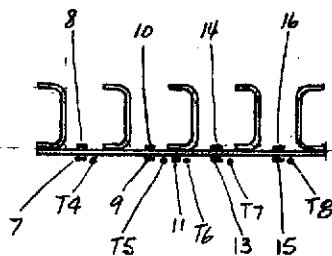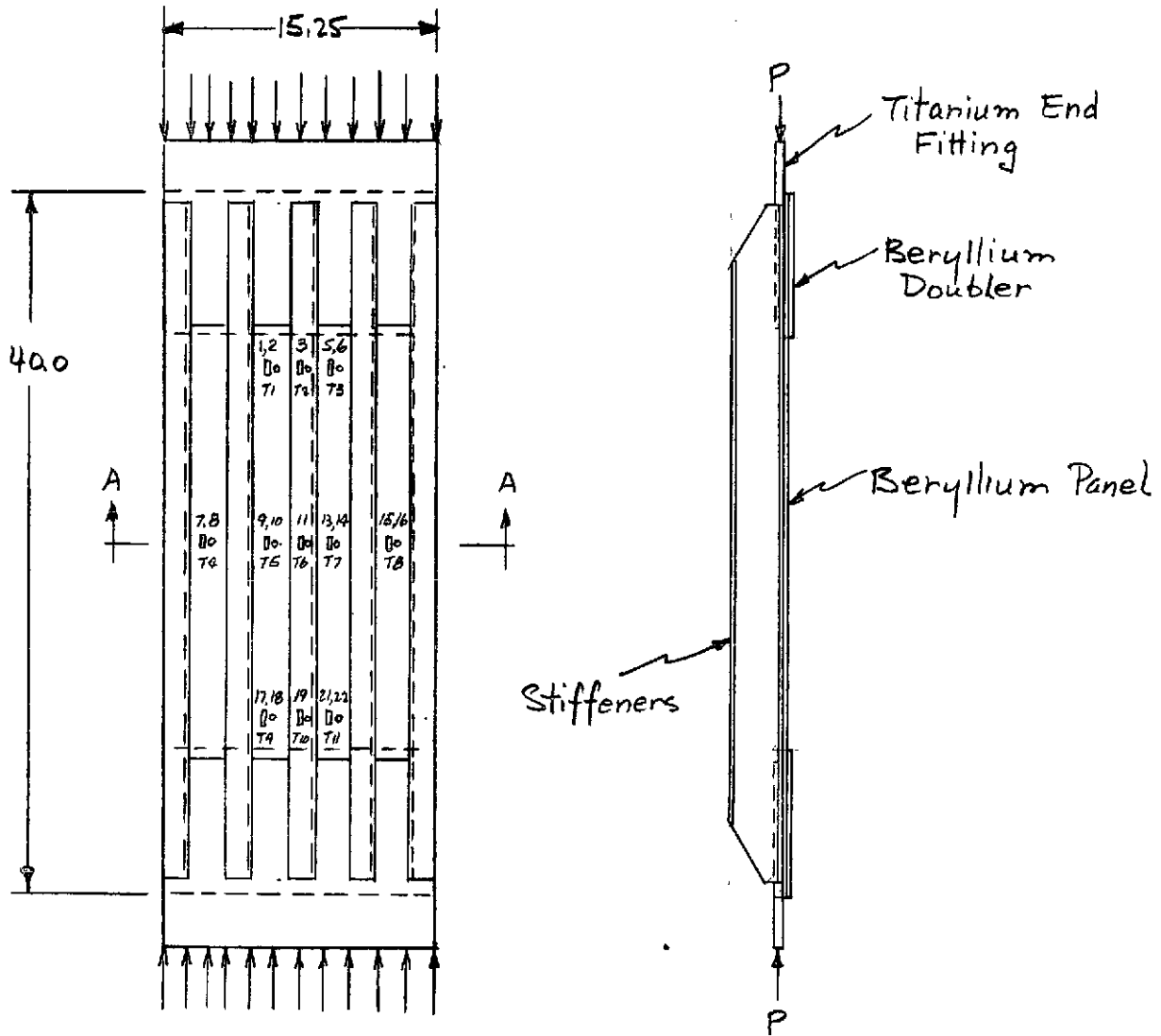
7,8 ; 9,10 ; .... are back-to-back strain gages

T4, T5, ... are thermocouples

SECT A-A

FIG. 1

T-4

UNIFORM LOAD TEST PANEL SKJ 201004

$$P_{Limit} = 5140 \text{ lbs/in} = 78,300 \text{ lbs}$$

$$P_{Ultimate} = 7200 \text{ lbs/in} = 110,000 \text{ lbs}$$

Test Temperatures:
Rm. Temp.
600°F

Side Fittings
See SKJ 201004

Personnel
Safety
Shield
(All Around)

Notes: 1. End fixtures must be capable of uniform loading on test panel.

2. Side fixtures must be maintained in-plane throughout testing.

TEST SET-UP
FIG. 2

FORM LMSC 392 B-2

UNIFORM LOAD TEST PANEL   SKJ 201004

TIME IN SECONDS

TIME-PHASED LOADING

FIG. 3

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

Prepared by: S. FUCHIGAMI   Date 4-27-72

Checked by: Date

Approved by: Date

Page 2   Temp.   Perm.

Title: TEST EVALUATION — UNIFORM LOAD SUBPANEL

Model:

Report No. EM B1-M5-1

SKJ 201004 TESTS (Cont'd)

STRAIN GAGE READINGS IN μ-INCHES

Gage #	AMBIENT TESTS		600°F TESTS			Failure (200%)
	50%	100%	50%	100%	140%	
1	340	690	320	730	1280	5780
2	265	560	300	540	940	2240
3	365	780	410	980	1850	5950
5	395	710	340	700	1350	5350
6	240	510	260	480	870	1400
7	295	600	330	640	950	4850
8	275	550	300	570	900	3550
9	290	590	320	600	790	910
10	260	540	280	560	740	930
11	280	550	290	610	800	1450
13	285	580	300	600	820	1660
14	265	550	280	560	750	1410
15	265	560	275	570	880	2000
16	245	520	250	490	810	1760
17	320	680	310	680	1350	3950
18	330	660	330	660	1150	3150
19	310	720	350	990	1800	5750
21	315	680	330	680	1400	5000
22	290	560	300	560	1000	1880

(Middle of Panel — indicated by arrow spanning gages 7 through 16)

$$100\% \text{ Limit Load} = 5140 \text{ lbs/in} = 78,300 \text{ lbs}$$

$$140\% \text{ Limit Load} = 7200 \text{ lbs/in} = 110,000 \text{ lbs}$$

$$\text{Failure load} = 163,000 \text{ lbs}$$

TABLE I

T-7

SKJ 201004 TESTS (Cont'd)

TABLE II

COMPARISON OF ACTUAL AND PREDICTED STRESSES

| GAGES * | 100% LIMIT LOAD | | | | 140% LIM. LOAD | |
| | AMBIENT | | 600°F | | 600°F | |
	MEASURED KSI	PREDICTED KSI	MEASURED KSI	PREDICTED KSI	MEASURED KSI	PREDICTED KSI
1-2	26.6	28.4	23.5	24.7	41.1	34.6
3	33.1	—	36.3	—	68.5	—
5-6	25.9	28.4	21.8	24.7	41.1	34.6
7-8	24.4	24.6	22.4	21.4	34.2	30.0
9-10	24.0	25.7	21.5	22.4	28.3	31.3
11	23.4	—	22.6	—	29.6	—
13-14	24.0	25.7	21.5	22.4	29.1	31.3
15-16	23.0	24.6	19.6	21.4	31.3	30.0
17-18	28.5	28.4	24.8	24.7	46.3	34.6
19	30.6	—	34.8	—	66.6	—
21-22	26.3	28.4	23.0	24.7	44.4	34.6

* Back-to-back readings are averaged.

TEST EVALUATION OF CONCENTRATED LOAD SUBPANEL, SKJ 201007

The testing of this subpanel was conducted similar to the uniform load subpanel tests, starting 5/10/72 and concluding 5/19/72 at the same facility. Figures 4, 5, and 6 depict the test configuration, the test set-up, and the loading requirements respectively. Based on the prior Uniform Load Subpanel Tests, the loading rate was reduced and the heating rate was changed to a longer soak time. The following tests were conducted.

1. Room temperature test to 50 percent limit load.

2. Room temperature test to 100 percent limit load.

3. Elevated temperature test to 50 percent limit load.

4. Elevated temperature test to 100 percent limit load.

5. Elevated temperature test to 140 percent limit load, hold for ten seconds, continue loading to failure.

The following panel and stiffener data are pertinent to this evaluation:

Panel and Stiffener Data (Ref. LMSC Tests)

Panel, Stiffeners: KBI Pressing #432P, Heat H-1532

	R. T.	600° F
F_{tu} =	70.2 KSI	42.2 KSI
F_{ty} =	51.1 KSI	38.9 KSI

Doublers: KBI Pressing #432, Heat H-1534

R. T.	600° F
F_{tu} = 65.9 KSI	42.2 KSI
F_{ty} = 47.4 KSI	38.6 KSI
F_{cy} = --	37.4 KSI
Elongation = 8 - 15% in 1"	48 - 50% in 1"
*Young's Mod. = 42.5 x 10^6 psi	37.0 x 10^6 psi

Panel Thickness	=	.139 - .141 in.	Ref.
Stiffener Thickness	=	.132 - .128 in.	"as-built"
Doubler Thickness	=	.134 - .135; .142 - .144 in.	Dimensions

*These are design values from EM B1-M2-1

Discussion

The concentrated load sub-panel SKJ 201007 was installed in a 500,000 lb Universal Testing Machine and subjected to a series of tests as specified in EM B1-M2-6A, Appendix B (Ref. 1). The 50% and 100% limit load tests at ambient temperatures were conducted without incident. Strain gage readings on one side of the $\overline{\mathbb{C}}$ of symmetry showed consistently higher readings than the opposite side - gages 37-38, 41-42, 43-44 read higher strains than gages 39-40, 47-48, 49-50 (see Table III). Additionally, the strain readings of gages 43-44 were considered abnormal. However, examination of the test specimen, its installation, and the gages disclosed no irregularities or structural anomolies; therefore the testing at elevated temperatures was allowed to proceed.

The rate of loading was reduced from 3640 lbs per second to 1820 lbs per second for the elevated temperature tests in order to provide greater control of the loading. Adequate temperature distribution in the panel and heat stabilization at 600° F were achieved with minimal complications. The 50% limit load test at temperature continued to show the higher strains on one-half of the specimen; however, the strains of gages 43-44 were improved. The 100% limit load test at 600° F likewise resulted in higher strains in the same one-half of the specimen but with good strain distributions. Comparison of actual and predicted stresses (Table IV) showed good correlation except for gages 45-46. The following tolerances are to be considered with respect to the strain gage data:

Strain gage tolerances = ± 50 μ-in ≃ ± 2 KSI

Strain gage readings = ± 10 μ-in ≃ ± .4 KSI

The final test to failure was conducted as follows: With the temperature stabilized at 600°F, load to 100% limit load (182,000 lbs), hold for 5 seconds, continue load to 140% limit load (255,000 lbs), hold for 10 seconds, and continue loading to failure. Failure occurred at 276,000 lbs (151% limit load).

The data in Table III show that 6 gages were reading above the yield of the material at 140% limit load (gages 38, 40, 41, 43, 47, 49) and that bending was occurring just above the horizontal doubler at approximately 240-250 seconds (gages 37-38, 39-40, 45-46, 47-48). At approximately 300 seconds it appears that this lower area of the panel failed in bending (see gages 43-44, 45-46, 47-48), the load then was carried by the stiffeners and panels in shear until failure occurred at 319 seconds.

Comparison of the measured stresses with the predicted stresses at 140% limit load (Table IV) do not show good correlation. In general, the measured stresses are higher than the predicted stresses in the areas without doublers, and in the doubled up areas, (gages 37-38, 39-40, 45-46) measured stresses were lower than the predicted stresses. Also at this load level, a discrepancy in the strain distribution is noted. (Gages 33-34 had consistently recorded higher strains than gages 35-36 throughout the 50% and 100% limit loads both at ambient and elevated temperatures; however, at 140% limit load, gages 35-36 recorded higher readings. Re-examination of raw test data verify that this reversal of magnitudes occurred and continued until failure. This may be explained by the hypothesis that as the panel yielded in the central lower portion as indicated by gages 43-44 and 47-48, the load redistributed to the stabilized outer portion, thereby causing the reversal in magnitudes. The lower readings in the doubled up areas are probably due to a combination of excessive bending in the areas of gages 45-46 and shear strain in the fasteners which may have permitted differential movement between the basic panel and the doublers.

The STAGS analysis (Ref. 4) predicts higher line loads at the center of the uniform takeout end of the subpanel than in the same location on the full size panel. The full size panel with its increased length and width provides a better transition and distributes its higher load much more effectively than the subpanel does for its load. Lineload predictions for the failure area just outside the uniform takeout fitting show higher values in the full sized panel than for the subpanel because the analysis assumes full effectivity for the doubler (which is also full width in the subpanel) in this region. However, since the doubler ends at the fitting, full effectivity is obviously not the case and the strain gage readings bear this out. This, of course, produces higher skin line loads and leads to the conclusion that, for the full size panel, skin line loads will be equal to or less than those encountered in the subpanel. The MSFC test panel, therefore, should demonstrate equal or higher loading capability than the subpanel tested at LMSC (151% design limit load).

SKJ 201007 - CONCENTRATED LOAD SUBPANEL

TEST CONFIGURATION & GAGE LOCATIONS

FIG. 4
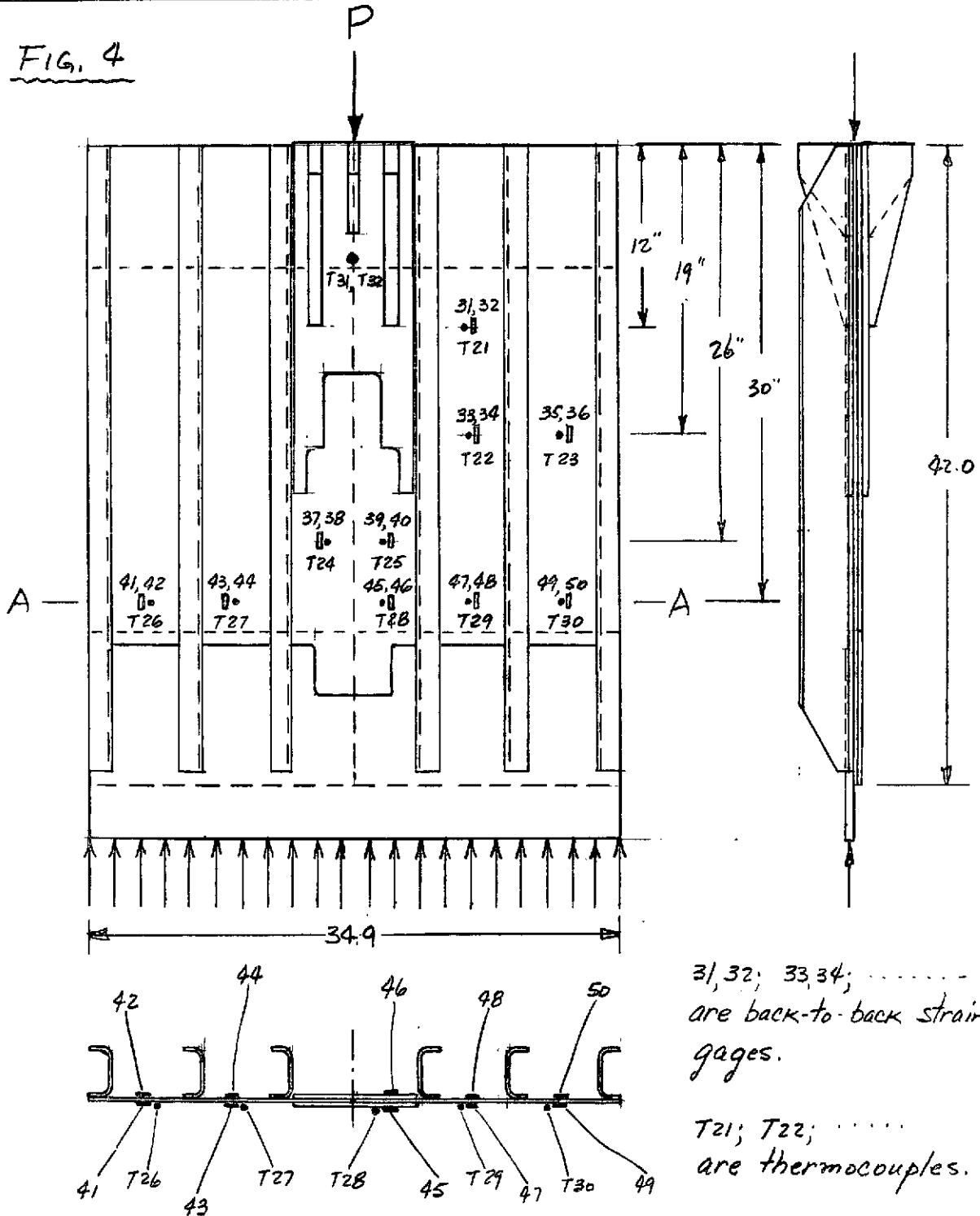
31,32; 33,34; ······ are back-to-back strain gages.

T21; T22; ······ are thermocouples.

SECT. A-A

T-12

CONCENTRATED LOAD SUB-TEST PANEL SKJ 201007

Personnel Safety Shield

P

Concentrated Load Fitting

Side Fittings
See SKJ 201007

SIDE FIXTURE   TEST PANEL   SIDE FIXTURE

END FIXTURE

$P_{Limit} = 182.000$ lbs

$P_{Ultimate} = 255,000$ lbs.

Test Temperatures:
Rm. Temp.
$600°F$.

Notes:

1. Load P must be applied over the complete end surface of the concentrated load fitting.

2. End fixture must be capable of uniform loading on test panel.

3. Side fixtures must be maintained in-plane throughout testing.

TEST SET-UP

FIG. 5

Ⅴ-13

CONCENTRATED LOAD SUB-TEST PANEL SKJ 20/007

TIME-PHASED LOADING

FIG. 6.

STRAIN GAGE READINGS IN μ-INCHES

GAGE #	AMBIENT TESTS		600°F TESTS		600°F TEST TO 140% L.L. & FAILURE				
	50%	100%	50%	100%	THERMAL STRAIN	100%	140%	FAILURE	TIME @ Fcy (SEC)
31	165	340	180	340	1590	350	500 (500 μ" max@ 270 sec.)	460	—
32	160	320	170	360	1330	350	590	710	—
33	220	480	240	490	1460	500	780	2260	290
34	210	370	170	320	1090	370	390	1070	318
35	140	330	185	350	1590	360	840	1410	305
36	125	290	170	290	1320	300	700	1100	318
37	255	490	225	430	900	430 (520 μ" max@ 250 sec)	500	360	—
38	250	520	260	550	1050	490	1010	1550	270
39	240	480	200	410	1040	400 (470μ" max@ 250 sec.)	420	280	—
40	250	500	230	470	1100	500	1020	1620	270
41	210	490	330	580	1580	580	1180	2910	265
42	195	430	300	560	1600	520	1000	2230	275
43	330	730	305	770	580	740	1840 (2230 μ" max@ 300 sec.)	1940	240
44	270	560	230	570	1180	520	660 (720 μ" max@ 300 sec.)	320	—
45	170	320	170	410	890	370	830	2890	305
46	155	310	150	250	800	250 (270 μ" max@ 230 sec)	60	+800	—
47	285	620	270	740	970	670	2120 (2590 μ" max@ 300 sec.)	1830	245
48	190	380	160	380	800	350 (400 μ" max@ 240 sec.)	270	+330	—
49	190	450	290	510	1600	520	1140	2860	265
50	165	420	260	510	1680	480	940	2160	280

100% Limit Load = 182,000 lbs reached at 215 seconds.
140%   "   "   = 255,000 "   "   "   270   "
   Failure "   "   = 276,000 "   "   "   319   "   = 151% Limit Load.

SKJ 201007 - CONCENTRATED LOAD SUBPANEL (Cont'd)

COMPARISON OF ACTUAL AND PREDICTED STRESSES

GAGES *	100% LIMIT LOAD			140% LIMIT LOAD		
	AMBIENT	600°F		600°F		
	MEASURED KSI	MEASURED KSI	PREDICTED KSI	MEASURED KSI	PREDICTED KSI	
31-32	14.1	13.0	14.3	20.2	20.0	
33-34	18.1	15.0	18.9	21.7	26.4	
35-36	13.2	11.9	13.7	28.5	19.2	
37-38	21.5	18.1	22.8	27.9	32.0	
39-40	20.8	16.3	22.8	26.6	32.0	
41-42	19.6	21.1	20.0	△40.4	28.0	
43-44	27.4	24.8	24.3	△46.2	34.0	
45-46	13.4	12.2	24.8	16.5	34.7	
47-48	21.3	20.7	24.3	△44.2	34.0	
49-50	18.5	18.9	20.0	△38.5	28.0	

* Back-to-back readings are averaged.

△ These stresses are above F_{cy}

TABLE IV

REFERENCES

1. EM Bl-M2-6A, "Structural Component Test Requirements Uniform Load Test Panel SKJ201004, Concentrated Load Test Panel SKJ201007, And Truss Component".

2. EM Bl-M2-1, "Beryllium Cross-Rolled Sheet Design Data at Room Temperature and 600° F".

3. Flash Report, TA 3277, 4/25/72, "Structural Test of Uniform Load Subpanel".

4. EM Bl-M2-4, "Analyses of the Concentrated Load and Uniform Load Panels With the STAGS Computer Code".

5. Flash Report, TA 3276, 5/22/72, "Structural Test of Concentrated Load Sub-Panel".

Appendix U

COMPILATION OF PROGRAM DRAWINGS

-7 END PLATE 2 REQD

-3 REF

-3 9 REQD

-9 SHIM AS REQD [8.]

-1 PLATE

-5 DOUBLER 2 REQD

-7 REF

29.0

24.08 7 EQ. SP.

1.44

3.00

86.0

78.65

80.0

125 EQ SP. TYP REF (.62)

15 EQ. SP. IN 26.25

1.38

.31

.68

-501 PANEL ASSY
SCALE: 1/4

LIMITED CALENDAR LIFE   LIMITED OPERATING LIFE

NOTES:

9. END CONFIGURATION OPTIONAL. MAY BE 45° CUT OFF AFTER FORMING.

8. TO COMPENSATE FOR OUT OF FLATNESS CONDITION BETWEEN -1 SHEET & -3 CHANNEL ADD SHIMS SO GAP BETWEEN PARTS DOES NOT EXCEED .003 BEFORE RIVETING.

7. DO NOT HAMMER RIVETS; ALL RIVETS MUST BE SQUEEZED.

6. ALL RIVET HOLES IN BERYLLIUM MUST BE CHAMFERED .010-.020 X 45° TO CLEAR RIVET RADIUS UNDER MANUFACTURED HEAD.

5. ALL HOLES IN BERYLLIUM MUST BE DRILLED; NOT PUNCHED.

4. FABRICATE BERYLLIUM PER PB-97.

3. BERYLLIUM PER LAC 07400B.

2. INSTALL FASTENERS PER APPLICABLE PARAGRAPHS OF PROCESS SPEC LAC 0581. PENDING OUTCOME OF RIVET INSTALLATION TESTING, SUPPLEMENTAL PROCESS CRITERIA SHALL BE DETERMINED.

1. MACHINE TITANIUM PARTS PER APPLICABLE PARAGRAPHS OF PROCESS SPEC LAC 3601.

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIP- TION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
AR		-9	SHIM [8]		.003 CRES SHT		
AR		MS 20615-5M	RIVET [7.]	MONEL			
2		-7	END PLATE	312 PLATE TITANIUM	MIL-T-9046 TYPE III COMP C ANNEALED		
2		-5	DOUBLER	BERYLLIUM	.124 ±.009 SHT [3]		
9		-3	CHANNEL	BERYLLIUM	.124 ±.009 SHT [3]		
1		-1	SHEET	BERYLLIUM	.124 ±.009 SHT [3]		
		-501					

PARTS LIST

SKJ201002 C

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD
	A	REVISED DETAIL DIMS & NOTES	10/2-71	
4/6	B	1.(REMOVED) DIM .63.		
3/6		2.(REMOVED) DIM .63 & DIM .68 (WAS) .63.	12/17/71	R.N. Sim
3/6		3.(REMOVED) DIM .66.		
2/F		4. DIM .110 MIN (WAS) .110 (2 PL)		
2/G		5. (ADDED) DIM .110 MIN.		
3B	C	1. IS: 32 PLACES(-7) WAS: 3.0	7-20-71	C.F. Rfh.d
6E		2: IS: 1.95 REF WAS: 1.95 TYP. REF		
BC		3: DIM .05 WAS: .50		
2C		4: IS 60° WAS 45°		

DETAIL A-A
SCALE: ↑
TYP TOP & BOTTOM

DETAIL B-B
SCALE: ↑
TYP TOP & BOTTOM

LIMITED CALENDAR LIFE   LIMITED OPERATING LIFE

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

COMPRESSION PANEL,
BERYLLIUM —
UNIFORM LOAD

| SIZE E | CODE IDENT | DRAWING NO SKJ201002 | REV C |

SCALE ½   SHEET 2 OF 2

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD
	A	REDESIGNED & REDRAWN	11 NOV 19	
	B	1. ADDED NOTE 13 TO FIELD CLIM	11 MAR 20	
7C		2. ADDED RIVET SPACING & FLAGS IN MAIN RIVET PATTERN VIEW		
12B		3. REPLACED DETAILED CALLOUT WITH DETAIL ASS'YS		
15C		4. REPLACED DETAILED CALLOUT WITH DETAIL ASS'YS		
13A		5. ADDED HOLE IN ITEM 2		
15F		6. CHANGED 45° TO 60°		
10C				

NOTE:

1. MACHINE TITANIUM PARTS PER APPLICABLE PARAGRAPHS OF SPEC LAC 3401.
2. INSTALL FASTENERS PER APPLICABLE PARAGRAPHS OF PROCESS SPEC 0581. PENDING OUTCOME OF RIVET INSTALLATION TESTING, SUPPLEMENTAL PROCESS CRITERIA SHALL BE DETERMINED.
3. BERYLLIUM PER LAC0T-400B.
4. FABRICATE BERYLLIUM PER PB-97.
5. ALL HOLES IN BERYLLIUM MUST BE DRILLED; NOT PUNCHED.
6. ALL RIVET HOLES IN BERYLLIUM MUST BE CHAMFERED .010 TO .020×45° TO CLEAR RIVET RADIUS UNDER MANUFACTURED HEAD.
7. DO NOT HAMMER RIVETS; ALL RIVETS MUST BE SQUEEZED.
8. TO COMPENSATE FOR OUT OF FLATNESS CONDITION BETWEEN ITEM 11 STIFFENER AND ITEM 5 WEB, ADD SHIMS SO GAP BETWEEN PARTS DOES NOT EXCEED .003 BEFORE RIVETING.
9. END CONFIGURATION OPTIONAL. MAY BE 45° CUT OFF AFTER FORMING.
10. WELD PER SPEC LAC 3853-020000.
11. MINIMUM FINISHED THICKNESS .125.
12. APPLIES TO ITEM 6.
13. THIS ASSEMBLY MAY BE MACHINED OUT OF A FORGED TITANIUM BILLET. THE MATERIAL SPEC FOR THE BILLET IS MIL-T-9047F, COMP C (ANNEALED).

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

COMPRESSION PANEL
BERYLLIUM — CONCENTRATED LOAD

SKC201001

DETAIL A

NOTE:

4. ALL FASTENER HOLES IN BERYLLIUM MUST BE CHAMFERED .010 TO .020 × 45° TO CLEAR FASTENER RADIUS UNDER MANUFACTURED HEAD.
3. ALL HOLES IN BERYLLIUM MUST BE DRILLED.
2. FABRICATE BERYLLIUM PER PB-97.
1. INSTALL FASTENERS PER APPLICABLE PARAGRAPHS OF PROCESS SPEC 0581.

P/L CONTINUED ON SHT 2

PARTS LIST

QTY REQD	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO.
2	-53	PLATE	5/8 PLATE BERYLLIUM	LAC-07-4008	4/5C	38
2	-51	PLATE	3/8 PLATE BERYLLIUM	LAC-07-4008	4/5C	37
1	-49	ANGLE	3 1/4 × 1 3/4 × 3/8 ANGLE BERYLLIUM	AMS 7901	4/5C	36
1	-47				4/5C	35
1	-45				4/5C	34
1	-43	ANGLE	3 1/4 × 1 3/4 × 3/8 ANGLE BERYLLIUM	AMS 7901	4/5C	33
2	-41	PLATE	3/8 PLATE BERYLLIUM	LAC-07-4008	4/5E	32
1	-39	PLATE	5/8 PLATE BERYLLIUM	LAC-07-4008	4/5E	31
1	-37	ANGLE	2 × 2 × 3/8 ANGLE BERYLLIUM	AMS 7901	4/5E	30
1	-35				4/5E	29
1	-33				4/5E	28
1	-31	ANGLE	2 × 2 × 3/8 ANGLE BERYLLIUM	AMS 7901	4/5E	27
1	-29	PLATE	3/16 PLATE BERYLLIUM	LAC-07-4008	4/5G	26
1	-27	ANGLE	1 1/2 × 1 1/2 × 1/4 ANGLE BERYLLIUM	AMS 7901	4/5G	25
1	-25		1 1/2 × 1 1/2 × 1/4 ANGLE BERYLLIUM		4/5G	24
1	-23		1 1/2 × 1 1/2 × 1/4 ANGLE BERYLLIUM		4/2G	23
1	-21	ANGLE	1 1/2 × 1 1/2 × 1/4 ANGLE BERYLLIUM	AMS 7901	4/7G	22
1	-19	PLATE	1/4 PLATE BERYLLIUM	LAC-07-4008	4/7G	21
1	-18	ANGLE	2 × 2 × 1/4 ANGLE BERYLLIUM	AMS 7901	4/7G	20
1	-17				4/7G	19
1	-15				4/8G	18
1	-13	ANGLE	2 × 2 × 1/4 ANGLE BERYLLIUM	AMS 7901	4/7G	17
2	-11	PLATE	3/8 PLT LOCKALLOY BE-38A1 COND. ANNEALED	LAC-07-4291	5/8H	16
2	-9				3/7A	15
2	-7				1/7A	14
2	-5				1/5H	13
2	-3				4/4A	12
2	-1	PLATE	3/8 PLT LOCKALLOY BE-38A1 COND. ANNEALED	LAC-07-4291	4/4H	11
1	-317	MEMBER B-F			3/5E	10
1	-315	MEMBER B-E			3/4E	9
1	-313	MEMBER B-D			3/5D	8
1	-311	MEMBER A-D			3/7E	7
1	-309	MEMBER D-E			3/6D	6
1	-307	MEMBER E-F			3/5D	5
1	-305	MEMBER C-F			3/7B	4
1	-303	MEMBER B-C			3/5F	3
	-301	MEMBER A-B			3/6F	2

FOLDOUT FRAME

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD

VIEW L-L
ROTATED 25° CCW

1.50 REF   1.50 REF   1.10

5 EQ SP AT 2.00 = 10.00

25 EQ SP AT 4.42 = 110.5

9 EQ SP AT 2.00 = 18.00

138.37 REF

6.67 REF

1.00

40 REQ (76)
.499 .506 DIA HOLE 40 PL

40 REQ (65)
.499 .506 DIA HOLE 40 PL

(4) REF

.376 .383 DIA 54 HOLES
54 REQ

VIEW K-K
ROTATED 45° CCW

1.00 REF   1.00 REF

1.00

26 EQ SP AT 5.78 = 150.3

152.83 (ITEM 48)

(8) REF

(66) .376 .383 DIA HOLE 56 PL
56 REQ

VIEW J-J
ROTATED 45° CW

1.00 REF   1.00 REF

1.37

27 EQ SP AT 5.44 = 146.9

149.73 (ITEM 31)

(10) REF

PARTS LIST

-317	-315	-313	-311	-309	-307	-305	-303	-301 -501	QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
	4										LS 8985-6	NUT			6/87	93
	4										AN960PD516	WASHER			6/87	92
	4										LS8954VTG-10	SCREW			6/87	91
																90
																89
12				4							LS 8985-8	NUT			6/5B	88
12				4							AN960PD416	WASHER			6/5B	87
12				4							LS8954VT8-16	SCREW 100° CSK			6/5B	86
																85
		108	90					73197			HK2002-10-10	BLIND BOLT ASSY	HI LOCK	HI SHEAR	5/5S	84
																83
																82
							126	73197			HK2002-12-22	BLIND BOLT ASSY	HI LOCK	HI SHEAR	5/6B	81
		162									HK2002-12-12				4/2B	80
						32					HK2002-12-18				1/8A	79
						54					HK2002-12-17				4/5C	78
						144					HK2002-12-24				1/8D	77
56				77							HK2002-16-16				2/BD	76
						44					HK2002-16-20				1/6A	75
						276					HK2002-16-28	BLIND BOLT ASSY			1/6C	74
						120					HL10VUE70-12-16	PIN & COLLAR			4/5G	73
						56					HL10VUE70-8-16	PIN & COLLAR			1/6G	72
						60					HL10VUE70-16-24				4/6F	71
			72								HL10VUE70-8-9				4/2F	70
																69
		108	156								HL10VUE70-10-10				5/7E	68
56											HL10VUE70-12-18				3/5B	67
84	54	246		72							HL10VUE70-12-12				4/LD	66
168			265					73197			HL10VUE70-16-16	PIN & COLLAR	HI LOCK	HI SHEAR CORP	1/7D	65
			2								-105	ANGLE	BERYLLIUM 4½x2x½x½ ANGLE	AMS 7901	1/7E	64
			2								-103	ANGLE	BERYLLIUM 4½x2x½x½ ANGLE	AMS 7901	1/6E	63
			2								-101	PLATE	BERYLLIUM ½ PLATE	LAC-07-4008	1/5E	62
			2								-99		BERYLLIUM ½ PLATE		5/6E	61
	1										-97		BERYLLIUM 5/16 PLATE		5/6E	60
	1										-95				5/6E	59
			2								-93	PLATE	BERYLLIUM 5/16 PLATE	LAC-07-4008	5/6E	58
	1										-91	ANGLE	BERYLLIUM 2x2x5/16 ANGLE	AMS 7901	5/6E	57
	1										-89				5/6D	56
	1										-87				5/6E	55
	1										-85		BERYLLIUM 2x2x5/16 ANGLE		5/6E	54
	1										-83		BERYLLIUM 2x2x¼ ANGLE		4/6E	53
	1										-81				4/6D	52
	1										-79				4/6E	51
	1										-77	ANGLE	BERYLLIUM 2x2x¼ ANGLE	AMS 7901	4/6E	50
	1										-75	PLATE	BERYLLIUM ¼ PLATE	LAC-07-4008	4/6D	49
			2								-73	PLATE	BERYLLIUM 3/16 PLATE		4/1B	48
	1										-71				4/7C	47
	1										-69	PLATE	BERYLLIUM 5/16 PLATE	LAC-07-4008	4/1B	46
	1										-67	ANGLE	BERYLLIUM 2x2x7/16 ANGLE	AMS 7901	4/1B	45
	1										-65				4/7C	44
	1										-63				4/7C	43
	1										-61		BERYLLIUM 2x2x¼ ANGLE		4/1C	42
4											-59	ANGLE	BERYLLIUM 4½x2x½x½ ANGLE	AMS 7901	4/5E	41
2											-57	PLATE	BERYLLIUM ½ PLATE	LAC-07-4008	4/5E	40
2											-55	PLATE	BERYLLIUM ½ PLATE	LAC-07-4008	4/5E	39

UNLESS OTHERWISE SPECIFIED DIM ARE IN INCHES. TOLERANCES ON:
FRACTIONS = ± 1/16
DECIMALS: .X = ± .1
.XX = ± .03
.XXX = ± .010
ANGLES = ± 2 DEG

INTERPRET DWG PER

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

BEAM ASSY, TRUSS
BERYLLIUM

SIZE E   CODE IDENT   DRAWING NO SKR-201017   REV

SCALE ¼   SHEET 2 of 6

NEXT ASSY   USED ON   APPLICATION   CCA/CU/FD

H

G

F

E

D

C

B

A

340.00

170.00

A

B

C

2

3

4.25 REF   2.12   3.19 REF   1.69

8.00 REF
4.00
7

5 ZA C

6.00 REF
3.00
10

A ZA

120.00

2.12
4.25 REF

8

9

8.00
16.00 REF

13 ZA

A ZA

8.00
16.00 REF

4

6

5

8.00 REF   4.00

12.00 REF   6.00

8.00
REF

D

E

F

120.00

240.00

SYMM

VIEW D-D

VIEW E-E

VIEW F-F

VIEW G-G

DETAIL B

H   G   F   E   D   C   B   A

(81) 32 REQ
.376 / .383 DIA 32 HOLES

(16) 2 REQ

(78) 32 REQ
.376 / .383 DIA 32 HOLES

5 EQ SP AT 1.37

(73) 28 REQ
.376 / .383 DIA 28 HOLES

(2) REF

11.00

5.60

.75

.06

21.20

6 EQ SP AT 1.84

1.00

6.25

10.12

1.00

.75

1.00

6.54

14.00

18.00

67°23' REF

38 EQ SP AT 2.78 (2 PL OPP)
(68) 78 REQ
.315 / .322 DIA 78 HOLES

(58) 2 REQ

(59)

(57)

(54)

(55)

(54)

(60)

4 PL 1.25
4 PL 1.25

8.00

8.00

38 EQ SP AT 2.78 = 105.50 (2 PL OPP)
(68) 78 REQ
.315 / .322 DIA. 78 HOLES

136.63

(7) REF

.315 DIA .322 HOLE 156 PL

(73) 32 REQ
.376 / .383 DIA 32 HOLES

1.00

(8) REF

23.25

2.78

1.00

(78)
.376 / .383 DIA HOLE 16 PL

45° REF

7 EQ SP AT 1.10

.75   27.00

(6) REF

.80

2.78

32 REQ (81)
.376 / .383 DIA HOLE 32 PL

6 EQ SP AT 1.73 = 10.4

23.75

32 REQ (78)
.376 / .383 DIA HOLE 32 PL

13.00 REF

3.30

1.00

5 EQ SP AT 1.90

9.63   9.00

3.00 2 PL
1.31 2 PL

1.31 TYP

3.00 TYP

2.38

8.44

13.88

26.50

(15) 2 REQ

(81) 24 REQ
.376 / .383 DIA HOLE 24 PL

H / 5/B

H / 5/B

DETAIL 6 / 5/D

6 / 6/D

8 EQ SP AT 2.00 = 16.00

38 EQ SP AT 2.71 = 103.0 REF

(68) 55 REQ
.315 / .322 DIA 55 HOLES

55 REQ (84)
.315 / .322 DIA 55 HOLES

8 EQ SP AT 2.00 = 16.00

1.0

VIEW H-H 3/AG

FOLDOUT FRAME

FOLDOUT FRAME

2

SECTION 12-12 2/8A

SECTION 13-13 2/8A

SECTION M-M 4/8B

SECTION N-N 4/8A

8 EQ SP AT 2.00 =16.0

38 EQ SP AT 2.71 =103.0

53 REQ (84) .315 DIA 53 HOLES .322

8 EQ SP AT 2.00 =16.0

(91) (92) (93) 4 REQ .315 .322 DIA HOLE CSK 100° X .80 DIA 4 PLACES

(68) 53 REQ .315 DIA 53 HOLES .322

5 EQ SP AT 2.00 =10.00

23 EQ SP AT 4.31 =99.2

(4) REF

(65) 37 REQ .499 DIA HOLE .506 37 PL

37 REQ (76) .499 DIA HOLE .506 37 PL

10 EQ SP AT 2.00 =20.00

(86)(87)(88) 2 REQ

(86)(87)(88) REF .499 DIA HOLE .506 CSK 100° X 1.06 DIA 2 PL

7 EQ SP AT 2.00

(86)(87)(88) REF

(9) REF

(86)(87)(88) .499 DIA HOLE .506 CSK 100° X 1.06 DIA 6 PL

9 EQ SP AT 2.00

(65) 28 PL .499 DIA HOLE .506 28 PL

28 REQ (76) .499 DIA HOLE .506 28 PL

(86)(87)(88) REF

14 EQ SP AT 6.58 =92.12

(86)(87)(88) REF

7 EQ SP AT 2.00

(86)(87)(88) REF

14 EQ SP AT 6.58 =92.12

(9) REF

(86)(87)(88) .499 DIA HOLE .506 CSK 100° X 1.06 DIA 6 PL

9 EQ SP AT 2.00

(65) 28 PL .499 DIA HOLE .506 28 PL

28 REQ (76) .499 DIA HOLE .506 28 PL

1.00

.80

1.50

2.00

2.00

2.00

SIZE	CODE IDENT	DRAWING NO.	REV
E		SKRZ01017	
SCALE 1/4			SHEET 6 OF 6

U-19

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD

VIEW L-L
CAP & WEB SECTION
NOT SHOWN FOR CLARITY
SCALE 1/2

SYM
ABOUT
C

PEEL SHIM TO FLUSH, -.003
BETWEEN FLANGE & FITTING

NOTES:

1. DO NOT HAMMER RIVETS, ALL RIVETS MUST BE SQUEEZED.
2. MACHINE PER LAC 3601
3. FABRICATE BERYLLIUM PER PS-97
4. ALL HOLES IN BERYLLIUM MUST BE DRILLED, NOT PUNCHED
5. INSTALL FASTENERS PER LAC 0881
6. ALL RIVET HOLES IN BERYLLIUM MUST BE CHAMFERED .010 TO .020 X 45° TO CLEAR RADIUS UNDER MANUFACTURED HEAD
7. TOLERANCES NOT ACCUMULATIVE
8. ODD DASH NO. SHOWN - NEXT HIGHER EVEN DASH NO. OPPOSITE
9. HEAT TREAT TO 180,000 PSI AFTER MACHINING

PARTS LIST

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
6		LS 8761-8-19	BOLT				54
28		HL10VUE379-12-21	PIN & COLLAR	HI LOCK	HI SHEAR CORP		53
16		HL10VUE379-12-18					52
8		HL10VUE379-12-13					51
44		HL10VUE379-12-10	PIN & COLLAR	HILOCK	HI SHEAR CORP		50
32		LS 8761-19-36	BOLT				49
4		-55	SHIM	.094 ALL LAMINATED AL SHIM STOCK	AMS 4013		48
3632		110680-6	RIVET				47
6912		110680-5	RIVET				46
18		LS 8999-4	WASHER				45
18		LS 8999-A4	WASHER				44
42		LS 8999-6	WASHER				43
42		LS 8999-A6	WASHER				42
16		LS 8999-8	WASHER				41
16		LS 8999-A8	WASHER				40
64		LS 8999-14	WASHER				39
64		LS 8999-A14	WASHER				38
18		LS 8861-4	NUT				37
42		LS 8861-6	NUT				36
16		LS 8861-8	NUT				35
48		LS 8861-12	NUT				34
18		LS 8761-4-20	BOLT				33
42		LS 8761-6-20	BOLT				32
10		LS 8761-8-18	BOLT				31
52		LS 8761-14-58	BOLT				30
1		-53	WEB	BERYLLIUM .180 MIN. SHEET	LAC-07-A008		29
2		-51	WEB	BERYLLIUM .180 MIN. SHEET			28
2		-49	WEB	BERYLLIUM .180 MIN. SHEET			27
2		-47	WEB	BERYLLIUM .180 MIN. SHEET			26
2		-45	WEB	BERYLLIUM .180 MIN. SHEET			25
2		-43	WEB	BERYLLIUM .180 MIN. SHEET	LAC-07-A008		24
3		-41	SHIM	.094 ALL LAMINATED S.ST. SHIM STOCK	AMS 4013		23
2		-39	SHIM				22
2		-37	SHIM				21
3		-35	SHIM	.094 ALL LAMINATED S.ST. SHIM STOCK	AMS 4013		20
2		-33	ANGLE, 5 X 3¼ X ⅛	MAKE FROM BERYLLIUM EXT.	AMS 7901		19
8		-31	ANGLE, 5 X 3¼ X ⅛	MAKE FROM BERYLLIUM EXT.			18
4		-29	ANGLE, 5 X 3¼ X ⅛	MAKE FROM BERYLLIUM EXT.			17
14		-27	ANGLE, 5 X 3¼ X ⅛	MAKE FROM BERYLLIUM EXT.	AMS 7901		16
2		-25	DOUBLER	1/2 PLATE BERYLLIUM	LAC-07-A008		15
2		-23	DOUBLER	1/2 PLATE BERYLLIUM	LAC-07-A008		14
2		-21	DOUBLER	1.000 PLATE BERYLLIUM	LAC-07-A008		13
2		-19	DOUBLER	.600 PLATE BERYLLIUM	LAC-07-A008		12
1		-17	END FITTING	4130 STEEL BILLET COND B	MIL-S-6758		11
3		-15	THRUST FITTING	4130 STEEL BILLET COND B	MIL-S-6758		10
3		-13	THRUST FITTING				9
1		-12	END THRUST FITTING				8
1		-11	END THRUST FITTING				7
1		-10	END THRUST FITTING				6
1		-9	END THRUST FITTING	4130 STEEL BILLET COND B	MIL-S-6758		5
2		-7	END COMP. CAP	MAKE FROM BERYLLIUM EXT.	AMS 7901		4
1		-5	CENTER COMP. CAP	MAKE FROM BERYLLIUM EXT.			3
2		-3	END TENSION CAP	MAKE FROM BERYLLIUM EXT.	AMS 7901		2
1		-1	CENTER TENSION CAP	MAKE FROM BERYLLIUM EXT.			1

INTERPRET DWG PER

UNLESS OTHERWISE SPECIFIED DIM ARE IN INCHES, TOLERANCES ON:
FRACTIONS = ± 1/16
DECIMALS : .X = ± .1
.XX = ± .03
.XXX = ± .010
ANGLES = ± 2 DEG

DATE 72 FEB 21
DWN C. J. ___
APVD
ENGRG
CHKR
APVD

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

SHEAR BEAM -
THRUST STRUCTURE
BERYLLIUM

SIZE	CODE IDENT	DRAWING NO	REV
		SKR 201020	L

SCALE 1/10 & NOTES   SHEET

NEXT ASSY | USED ON
APPLICATION
CONTR
CCA/CI/FD

REVISIONS
| ZONE | LTR | DESCRIPTION | DATE | APVD |

H

SEE DETAIL
SHT 4 - ZONE 5C

10
REF

6
REF

12
REF

10

SEE -1 DETAIL
SHT 5 - ZONE 2C

12

15

SEE -3 DETAILS
SHT 5 - ZONE 3B

10
REF

7

19
18
29
34

G

SEE DETAIL
SHT. 4 - ZONE 5C

8
REF

17

9

16

SEE DETAILS
SHT 5 ZONE 2B

17

SEE DETAILS
SHT 5 ZONE 2B

16

19
REF

18
REF

19
REF

18

SEE DETAILS ON
- 5, ZONE 2B

5

SYM
ABOUT
E

182.55 BASIC

42.55 BASIC

7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7

F

12
REF

12
REF

.760
BASIC

55.00
BASIC

E

29
REF

28
REF

27
REF

26
REF

25
REF

24
REF

D

ANGLES & FITTINGS NOT
SHOWN FOR CLARITY

13
REF

13
REF

13
REF

C

FWD
POSTS
NO 1

ANGLE
NO.
33

ANGLE
NO.
32

ANGLE
NO
31

ANGLE
NO.
30

ANGLE
NO
29

THRUST
POST
NO.4

ANGLE
NO
27

ANGLE
NO
26

ANGLE
NO
25

ANGLE
NO
24

ANGLE
NO
23

ANGLE
NO
22

ANGLE
NO
21

ANGLE
NO
20

THRUST
POST
NO. 3

ANGLE
NO
6

ANGLE
NO
7

ANGLE
NO
8

ANGLE
NO
9

ANGLE
NO
10

ANGLE
NO
12

ANGLE
NO
13

ANGLE
NO
14

THRUST
POST
NO. 5

ANGLE
NO
15

ANGLE
NO
16

ANGLE
NO
17

ANGLE
NO
18

ANGLE
NO
19

END
POSTS
NO. 2

B

13

14

4

11

9
REF

13
REF

3
SEE -5 DETAIL
SHT. 6 - ZONE 6C

DIMS. TYP. FOR
ALL CAP PLATES

SEE -7 DETAIL
SHT. 5 - ZONE 3B

30
38
39
34

A

SIZE	CODE IDENT	DRAWING NO	REV
E		SKR 201020	
SCALE			SHEET 2 of 5

SKR 201020

DETAIL C 18/20
1/2 SCALE

DETAIL 12 17/20

DETAIL A 7/20
1/2 SCALE

DETAIL 13 7/20
TYPICAL ATTACH PATTERN
FOR UPPER TENSION CAP
TYPICAL ATTACH PATTERN FOR
ANGLES NO. 8, 9, 12, 13, 14

SIZE	CODE IDENT	DRAWING NO	REV
E		SKR 201020	L
SCALE			SHEET 3 OF 3
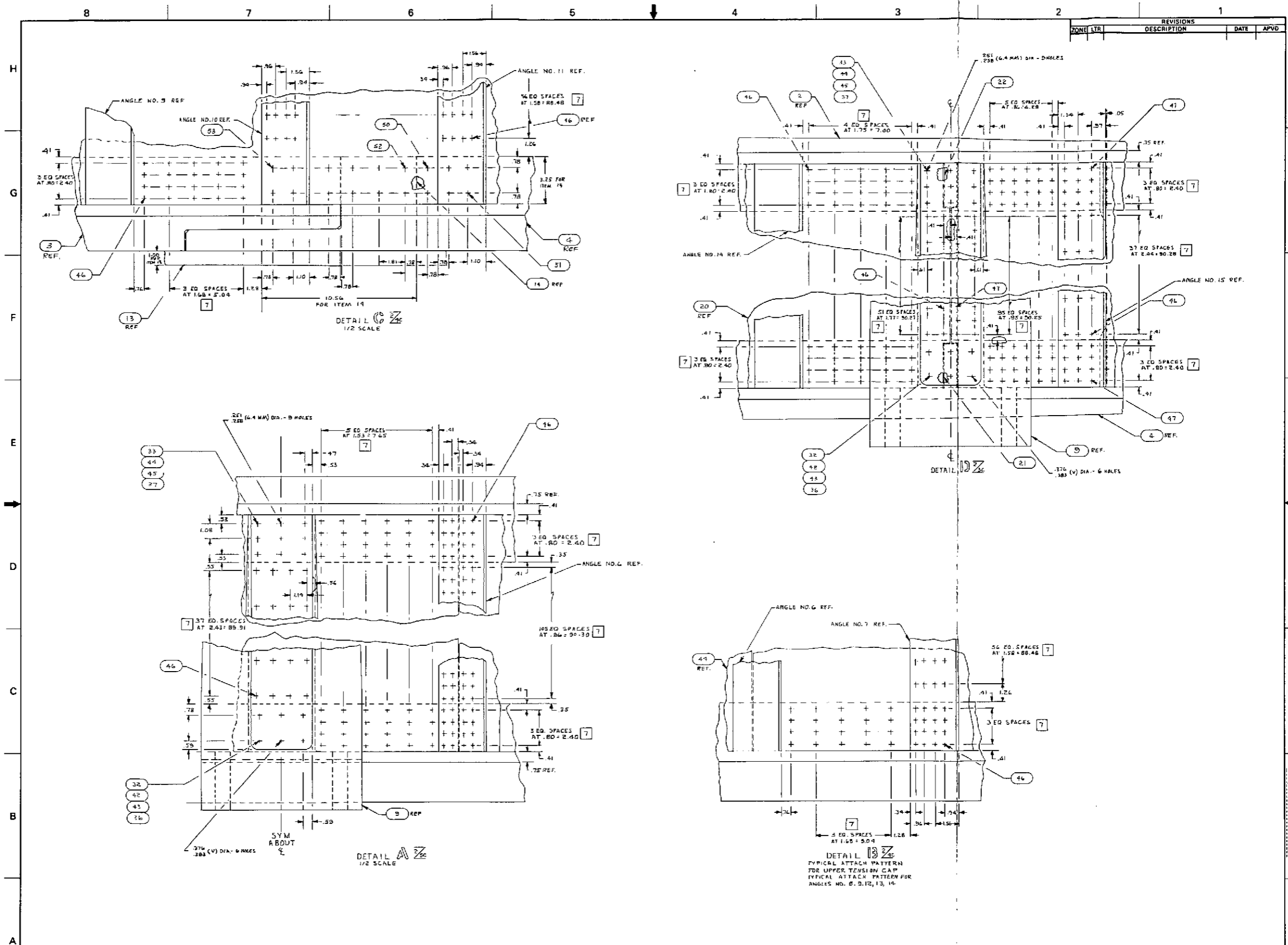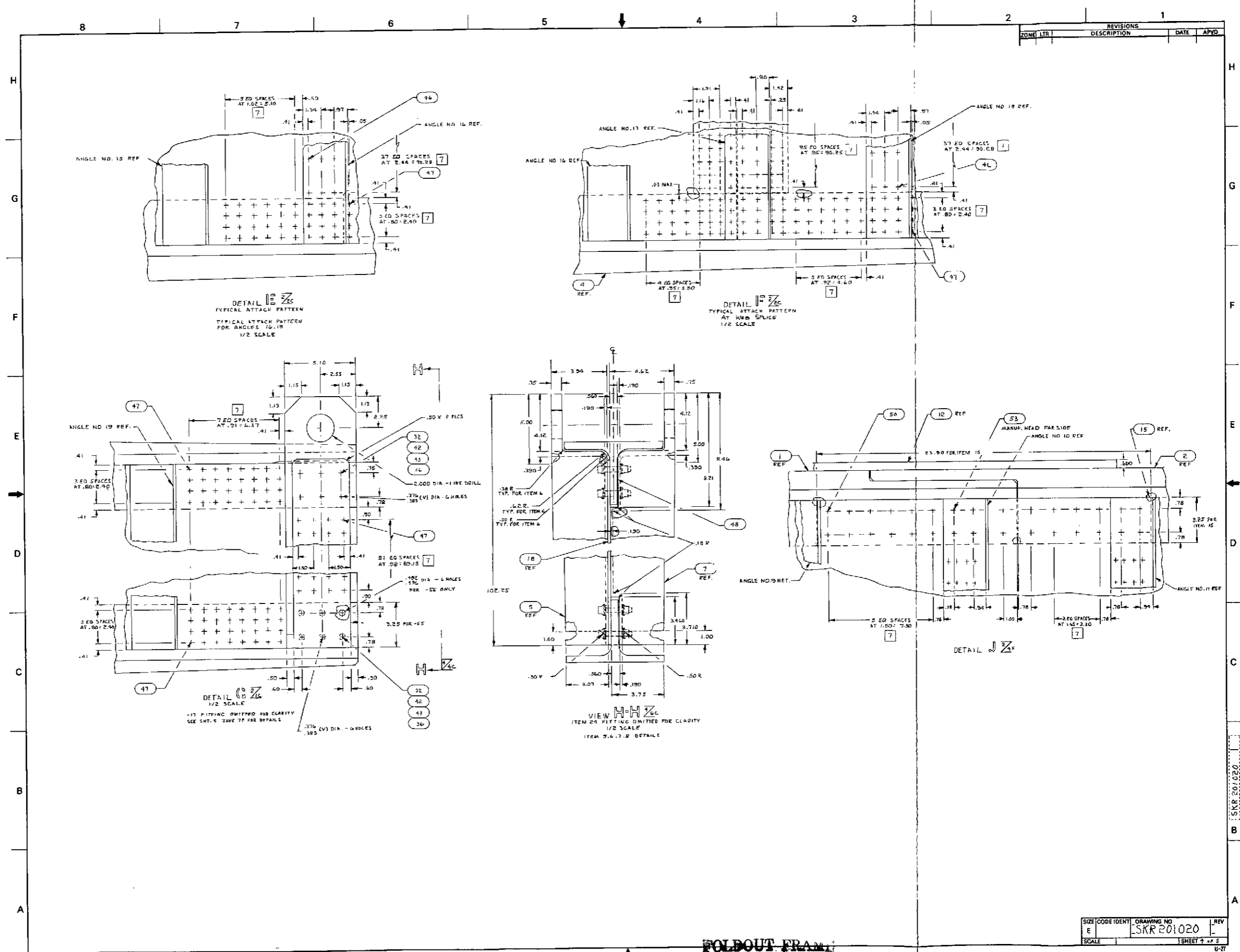
REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD

DETAIL I▯ $\frac{Z}{ZC}$
TYPICAL ATTACH PATTERN
TYPICAL ATTACH PATTERN
FOR ANGLES 16,18
1/2 SCALE

DETAIL I▯ $\frac{Z}{ZC}$
TYPICAL ATTACH PATTERN
AT WEB SPLICE
1/2 SCALE

DETAIL I▯ $\frac{Z}{ZC}$
1/2 SCALE
-17 FITTING OMITTED FOR CLARITY
SEE SHT. 5 ZONE 7F FOR DETAILS

VIEW H-H $\frac{Z}{ZC}$
ITEM 24 FITTING OMITTED FOR CLARITY
1/2 SCALE
ITEM 5,6,7,8 DETAILS

DETAIL J $\frac{Z}{Z4}$

FOLDOUT FRAME

FOLDOUT FRAME

2

DETAIL & INSTALLATION OF -17
1/2 SCALE

DETAIL K
TYP FOR LOWER EDGE
OF ITEM 25 & 26 WEBS

DETAIL -37 SHIM
FULL SCALE

DETAIL -35 SHIM
FULL SCALE

ITEM 2
DETAIL OF -3
1/4 SCALE

ITEM 4
DETAIL OF -7
1/4 SCALE

SYM. ABOUT ℄

ITEM 1 & 3
DETAIL OF -1 & -5
1/4 SCALE

DETAIL OF WEBS
1/10 SCALE

DETAIL OF -27, -29, -31 & -33
1/2 SCALE

FOR -29 ONLY
1/2 SCALE

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD
	A	REVISED DETAIL DIMS & NOTES	10/27/71	
P/L	B	DELETED ITEMS 11 & 12 & 17; ADDED ITEMS 18 & 19;	11/4/71	
B/C		ADDED NOTE 14; DELETED NOTES 7 & 8; SEE SHTS 2, 3 & 4 FOR ADDITIONAL CHGS	11/10/71	
	C	1. IN GEN. NOTES DELETED NOTE 14 & ADDED NOTES 13 & 15.		
		2. IN LM .124±.009 (WAS) .110 FOR ITEMS 1, 2 & 3.		
		3. IN LM MAT'L (WAS) ½ X ¾ BAR FOR ITEM 9, MAT'L (WAS) ⅛X⅞ FOR ITEM 18, MAT'L (WAS) ⅝ X 1¾ FOR ITEM 19.	12/14/71	R.W.Sims
		4. IN LM (ADDED) ITEMS 20, 21 & 22.		
		5. REVISED TITLE	3/20/72	
P/L	D	1. IN L/M, ITEM 6: 15 REQ'D WAS: 11 REQ'D	3/20/72	

3-21-72
Assembled wt = 285 lbs.

PARTS LIST

QTY REQD -505	QTY REQD -503	QTY REQD -501	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
4				-33	BAR	¼ X 2 BAR	1020 STEEL		22
12				-31	SHIM	LAM. AL SHIM .032 (.003 LAM.)	LAC-07-605 TYPE I		21
6				-29	SHIM	LAM. AL SHIM .032 (.003 LAM.)	LAC-07-605 TYPE I		20
	4			-27	SPACER	⅛ X 1¾ BAR	1020 STL		19
	AR			-25	ASBESTOS	⅜ X ⅛ STRIP X 15 FT	COML		18
	AR			-23	SHIM	.003 SHEET	CRES		17
1				-503	TEST FIXTURE				16
1				-501	TEST PANEL				15
	36				NUT	7/16-20 UNF HEX	STEEL		14
	36				BOLT	AN7-17 OR EQUIV.			13
	2			-21	SHIM	LAMINATED STEEL	.125 THICK .003 LAMINATIONS		12
	2			-19	SHIM	LAMINATED STEEL	.188 THICK .003 LAMINATIONS		11
	2			-17	BAR	½ X 2 BAR	1020 STL		10
	2			-15	SPACER	¾ X 1¾ BAR	1020 STL		9
	2			-13	ANGLE	2 X 3 X ½ ANGLE	ASTM-A36		8
11				-11	THERMOCOUPLE				7
19				-9	STRAIN GAGE				6
	AR			MS20G15-5M	RIVET				5
	2			-7	END PLATE	.312 PLATE TITANIUM	MIL-T-9046 TYPE III COMP C ANNEALED		4
	2			-5	DOUBLER	BERYLLIUM	.124±.009 SHT		3
	5			-3	CHANNEL	BERYLLIUM	.124±.009 SHT		2
	1			-1	PLATE	BERYLLIUM	.124±.009 SHT		1

NOTES:

15. MATCH DRILL HOLES IN ITEMS 8, 9, 10 & 20.
13. MATCH DRILL HOLES IN ITEMS 8, 19, 21 & 22.
~~14. BOND ITEM 18 TO ITEMS 8 & 10 PER SPEC LAC 30-4110.~~
12. END CONFIGURATION OPTIONAL. MAY BE 45° CUT OFF AFTER FORMING.
11. TO COMPENSATE FOR OUT OF FLATNESS CONDITION BETWEEN -1 PLATE & -3 CHANNEL ADD SHIMS SO GAP BETWEEN PARTS DOES NOT EXCEED .003 BEFORE RIVETING.
10. DO NOT HAMMER RIVETS; ALL RIVETS MUST BE SQUEEZED.
9. ATTACH THERMOCOUPLES AS CLOSE AS POSSIBLE TO THE STRAIN GAGES.
~~8. ADD OR SUBTRACT SHIMS AS REQ'D TO ATTAIN A .005 TO .010 CLEARANCE BETWEEN CLAMPING BARS & THE -501 ASSY.~~
~~7. APPLY SOLID FILM LUBRICANT PER SPEC LAC 24-4334 TYPE I CLASS 3 TO TOP & BOTTOM SURFACES OF -501 ASSY FOR A .25 MIN. IN FROM EDGES AND FOR THE LENGTH OF THE TEST FIXTURE (18.6)~~
6. ALL RIVET HOLES IN BERYLLIUM MUST BE CHAMFERED .010-.020 X 45° TO CLEAR RADIUS UNDER MANUFACTURED HEAD.
5. ALL HOLES IN BERYLLIUM MUST BE DRILLED; NOT PUNCHED.
4. FABRICATE BERYLLIUM PER PB-97.
3. BERYLLIUM PER SPEC. LAC 074008.
2. INSTALL FASTENERS PER APPLICABLE PARAGRAPHS SPEC LAC 0581, PENDING OUTCOME OF RIVET INSTALLATION TESTING, SUPPLEMENTAL PROCESS CRITERIA SHALL BE DETERMINED.
1. MACHINE TITANIUM & STEEL PARTS PER APPLICABLE PARAGRAPHS OF PARAGRAPHS OF PROCESS SPEC 3601.

UNLESS OTHERWISE SPECIFIED DIM ARE IN INCHES. TOLERANCES ON:	DATE 14 OCT 71	LOCKHEED MISSILES & SPACE COMPANY A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION SUNNYVALE, CALIFORNIA
FRACTIONS = ± 1/16	DWN	
DECIMALS: .X = ± .1	APVD	COMPRESSION SUB PANEL, BERYLLIUM- UNIFORM LOAD
.XX = ± .03	ENGRG	
.XXX = ± .010	CHKR	
ANGLES = ± 2 DEG	APVD	

NEXT ASSY	USED ON	CONTR	SIZE E	CODE IDENT	DRAWING NO SKJ201004	REV D
APPLICATION		CCA/CI/FD		SCALE ½		SHEET 1 OF 4

46.00 REF

40.00

38.65

3.00

①

③
2 REQD

-501

.158 DIA HOLE
.166

⑤ | 10 | 2 | 5. | 6.
AS REQD

④ 2 REQD

.62

14.00
8 EQ. SP.

15.25

② 5 REQD

7 .25

7 .25

.25 7

.25 7

17 AS REQD
11.

SECTION C-C

SKJ201004 D

LIMITED CALENDAR LIFE   LIMITED OPERATING LIFE

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD
	A	REVISED DETAIL DIMS & NOTES	10/27/71	
3/C	B	.68 WAS .63; REMOVED		
		.63 TYP 2 PLACES;		
5/B		18 PLACE (-7) WAS 30;		
4/G		1.95 3 PLACES WAS 7;		
4/G		1.50 3 PLACES WAS 7;		
4/F		3.44 3 PLACES WAS 7.	11/12/71	BSF
3/C		1. DIM .05 (WAS) .50		Sigma
2/C		2. DIM .110 MIN (ADDED)		
3/F	C	3. MIN (ADDED IN 2 PL)	12/14/71	
1/A		4. REVISED TITLE		
2C	D	1. IS: 60° WAS: 45°	3/20/72	C.J.
2C		2. IS: .75 WAS: 1.0		ROLAND
3B		3. IS: .376/.383 DIA		
		30 PLACES. WAS: .437/		
		.444 DIA. 18 PLACES		
8E		4. IS: 1.95 REF. WAS:		
7E		1.95 TYP REF.		
8D		5. IS: 5 PLACES. WAS:		
		3 PLACES		

DETAIL A-A
SCALE: ½
TYP TOP & BOTTOM

DETAIL B-B
SCALE: ½
TYP TOP & BOTTOM

SK J201004

FOLDOUT FRAME

FOLDOUT FRAME

PARTS LIST

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

COMPRESSION SUB PANEL,
BERYLLIUM - UNIFORM
LOAD

SIZE E   CODE IDENT   DRAWING NO SK J201004

U-35

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD
	A	REVISED DIMS & REVISED NOTES	10 JUN 71	
1/E	B	.50 WAS 5/16 STK;		
2/C		.62 WAS .18 STK;		
2/D		ITEM 12 DELETED;		
4/B		9 WAS 4		
7/A		ADDED ITEM 17;	11/17/71	
6/D		ITEM 19 WAS ITEM 11		
3/C		ITEM 18 WAS ITEM 11		
	C	THIS SHEET REVISED	12/14/71	
	D	NO CHANGES	3-20-72	

DETAIL ITEM 22

.437 .444 DIA — 3 HOLES [13]

2 EQ SP AT 2.44 = 4.88
6.38
.75
2.00
.75
.50 REF

DETAIL ITEMS 9 & 20
2 REQD EA

.437 .444 DIA 8 HOLES [15]
23.60
7 EQ SP AT 3.16 = 22.10
.032 REF FOR ITEM 20
20 REF
.375 REF FOR ITEM 9
9 REF

DETAIL ITEM 10 — 2 REQ

.437 .444 DIA 8 HOLES [15]
7 EQ SP AT 3.16 = 22.10
23.60
2.00
.50 REF

DETAIL ITEMS 19 & 21
4 REQD EA

.032 REF FOR ITEM 21
21 REF
1.75
.50 REF FOR ITEM 19
19 REF
6.38
2 EQ SP AT 2.44
.437 DIA 3 HOLES [13] .444

22 REF
8 REF
18 REF
10 REF
9 REF
22 REF

38.60

3.70 2 PL
7.50
10.0
7.50

20.0

10.0

.75

38.60 REF

.437 DIA 14 HOLES .444 THRU ITEM 8 MATCH DRILL WITH ITEMS 9, 10, 20, & 19, 21 & 22

-503 & -505 ASSY

13 14 28 REQD EA

8 REF

-505 ASSY
SECTION D-D

MOUNTING ANGLES SHALL BE IN A COMMON PLANE WITHIN .020

-501 ASSY REF

8 REF

8 2 REQ

2.00
.75

SECTION D-D
SHOWN MOUNTED IN TEST FIXTURE

MOUNTING STRUCTURE REF

19 4 REQ

18 4 PLACES

22 REF

21 12 REQ

22 4 REQ

13 14 REF

-501 ASSY

8 REF
9 2 REQD
20 6 REQ
10 2 REQ

.37
1.06
1.06 5 PL
1.06 6 PL
1.06
.37

6
6
6
6
6

7
7 9
7

SECTION D-D

PARTS LIST

QTY REQD	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIP- TION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO

SKJ 201004 D

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APVD
	A	1. ADDED GEN. NOTE 16	3-26-72	
		2. ADDED NOTE 16 CALLOUT IN M/L FOR		
		ITEMS 11 AND 12		
		3. ITEM 25 WAS 28 REQD		
		ITEM 32 WAS 32 REQD		
		4. ADDED 12.00 DIAM.		
		5. CHANGED TERMINATION OF 2 AT ARROW HEAD		

DETAIL I⁻¹⁵
SCALE 1/1

28 SHOWN REF
29 OPP REF

16

26 SHOWN
27 OPP

DETAIL I⁻⁹
SCALE 1/2

SEC ID-ID
SCALE 1/2

.252 / .266 DIA-92 HOLES

14 EQ SP AT 1.00 = 14.00

5 EQ SP AT .97

6 EQ SP AT 1.00

NOTES:

A1 16. THIS ASSEMBLY MAY BE MACHINED OUT OF A FORGED TITANIUM BILLET. THE MATERIAL SPEC. FOR THE BILLET IS MIL-T-9047 F, COMPOSITION 6 (ANNEALED).

15. ALL RIVET HOLES IN BERYLLIUM MUST BE CHAMFERED .010 TO .020 X 45° TO CLEAR RIVET RADIUS UNDER MFG HEAD.

14. INSTALL FASTENERS PER APPLICABLE PARAGRAPHS OF PROCESS SPEC 0581. PENDING OUTCOME OF RIVET INSTALLATION TESTING, SUPPLEMENTAL PROCESSES WILL BE DETERMINED.

13. MOUNT STRAIN GAGES BACK TO BACK ON EACH SIDE OF PANEL.

12. ALL HOLES IN BERYLLIUM MUST BE DRILLED, NOT PUNCHED.

11. TO COMPENSATE FOR OUT OF FLATNESS CONDITION BETWEEN -1 PLATES & -11 CHANNELS ADD SHIMS SO THE GAP BETWEEN PARTS DOES NOT EXCEED .003 BEFORE RIVETING.

10. WELD PER SPEC LAC 3853-050200.

9. ATTACH THERMOCOUPLES AS CLOSE AS POSSIBLE TO THE STRAIN GAGES.

8. END CONFIGURATION OPTIONAL. MAY BE 45° CUT OFF EITHER IN FLAT PATTERN OR AFTER FORMING.

7. PEEL LAMINATIONS OF SHIMS AS REQUIRED TO OBTAIN DESIRED PANEL EDGE RESTRAINT.

6. MINIMUM FINISHED THICKNESS .125.

5. APPLIES TO ITEM 4 ONLY.

4. FABRICATE BERYLLIUM PER PB-97.

3. BERYLLIUM PER LAC 07-4008.

2. MACHINE TITANIUM PARTS PER APPLICABLE PARAGRAPHS OF SPEC LAC 3601.

1. DO NOT HAMMER RIVETS; ALL RIVETS MUST BE SQUEEZED.

NOTE:

PARTS LIST

QTY REQD -306	QTY REQD -305	QTY REQD -503	QTY REQD -501	QTY REQD -505	QTY REQD -503	QTY REQD -501	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL DESCRIPTION OR NOTE	MATERIAL SPECIFICATION	ZONE	ITEM NO
					12			-45	SHIM	LAM. AL SHIM .032 (.003 LAM) TYPE I	LAC-07-605	3A	35
					2			-43	SPACER	3/8 X 2 BAR	1020 STEEL	1A	34
					2			-41	INSULATOR	1/8 THICK COML ASBESTOS		6A	33
					2			-39	SPACER	1/4 X 2 BAR	1020 STEEL	1A	32
					6			-38	SHIM	LAM. AL SHIM .032 (.003 LAM.) TYPE I	LAC-07-605	2A	31
					1			-37	ANGLE	2 X 3 X 1/4 ANGLE	ASTM-A36	1H	30
			1					-306	WELD ASSY			1SH	29
			1					-305	WELD ASSY			1SH	28
1								-36	FLANGE	.250 PLATE Ti-6AL-4V	MIL-T-9046 TYPE III COMP C ANNEALED	1H	27
	1							-35	FLANGE	.250 PLATE Ti-6AL-4V	MIL-T-9046 TYPE III COMP C ANNEALED			26
			30						NUT - HEX	3/8-24 UNF	STEEL	3C	25
			30						BOLT-HEX.HD.	3/8-24UNFX 1 1/2 LG	STEEL	3C	24
			20					-33	STRAIN GAGE			3H	23
			12					-31	THERMOCOUPLE			3G	22
				1				-503				3C	21
				1				-501				3D	20
			2					-29	INSULATOR	1/8 THICK COML ASBESTOS		7A	19
			2					-27	BAR	1/2 X 2 BAR	1020 STEEL	3D	18
			2					-25	BAR	1/2 X 2 BAR	1020 STL	7D	17
1	1							-23	FLANGE	.375 PLATE Ti-6AL-4V	MIL-T-9046 TYPE III COMP C ANNEALED	7C	16
			AR					MS20615-8M	RIVETS			3E	15
			AR					MS20615-6M	RIVETS			3D	14
			1					-303	BASE ASSY	16		1CC	13
			1					-301	BASE ASSY	16		1CC	12
			1					-21	DOUBLER	.140 +.012/-.010 SHEET	3 6	2G	11
		2						-19	GUSSET	.25 PLATE TITANIUM	MIL-T-9046 TYPE III COMP C ANNEALED	1D	10
								-17	RIB-CENTER	.75 PLATE TITANIUM		1D	9
		1	1					-15	RIB-OUTER	1.00 PLATE TITANIUM		1D	8
		2	2					-13	BASE PLATE	.500 PLATE TITANIUM	MIL-T-9046 TYPE III COMP C ANNEALED		7
		1	1					-11	CHANNEL	.140 +.012/-.010 SHEET	3 6	2D	6
			6					-9	DOUBLER	.140 +.012/-.010 SHEET	3 6	2SG	5
			1					-7	LOADING PLATE	.375 PLATE TITANIUM	MIL-T-9046 TYPE III COMP C ANNEALED		4
			1					-5	DOUBLER-BACK	.140 +.012/-.010 SHEET	3 6	3E	3
			1					-3	DOUBLER-FRONT	.140 +.012/-.010 SHEET	3 6	3E	2
			2					-1	PLATE	.140 +.012/-.010 SHEET	3 6	3G	1

INTERPRET DWG PER

UNLESS OTHERWISE SPECIFIED DIM ARE IN INCHES. TOLERANCES ON
FRACTIONS = ± 1/16
DECIMALS: .X = ± .1
.XX = ± .03
.XXX = ± .010
ANGLES = ± 2 DEG

DATE 71 DEC. 2
DWN
APVD
APVD
ENGRG
CHKR
APVD
CONTR
CCA/CI/FO

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

COMPRESSION SUB PANEL, BERYLLIUM-CONCENTRATED LOAD

SIZE E   CODE IDENT   DRAWING NO SKJ 201007   REV LA

SCALE NOTED   SHEET 1 OF 4

NEXT ASSY   USED ON
APPLICATION

.437
.444 DIA ~ 36 HOLES

2.50
1.00

8.00

34.90 REF

SEC A-A

FOLDOUT FRAME 1

SIZE	CODE IDENT	DRAWING NO.	REV
E		SKJ 201007	A
SCALE 1/2		SHEET 2 OF 4	

VIEW C-C $\frac{2}{1C}$

SEC B-B $\frac{3}{SH}$

FOLDOUT FRAME 1

FOLDOUT FRAME 2

H   G   F   E   D   C   B   A

SYMM

(30)

(20)

(17)   J   (18)   K   (17)

(17)   (21)   (24) (25)

5.28 2 PL   8.42 2 PL   .75   7 EQ SP AT 3.16   .75

2 PL .75 2.44   6.38 2 PL   .75 2 PL

.437 .444 DIA HOLE – 28 PL

23.60

-505 ASSY

J   K

SEC G-G
SCALE 1/2

(19) REF
(17) REF   .38
2.00   .75 1.75
[7] (35)   (24) REF
(25) REF
MOUNTING STRUCTURE REF   (32)   (31) REF

(17)   (18)   (17)

(19)

(38)   (33)   (30) (31)

38.60

SEC H-H

REF (19)   .37   (24) REF
(25) REF
2.00 .75 1.75   (31) REF
REF (17)   (32)
[7] (35)
SEC J-J

(33) REF   (24) REF
(25) REF
.37
2.00 .75 1.75   (31) REF
REF (18)   (34)
[7] (36)   **SEC K-K**

FOLDOUT FRAME
1

FOLDOUT FRAME
2

Appendix V

EM B1-M2-12

FINITE ELEMENT MODEL AND WEIGHT COMPARISON
OF CANDIDATE MATERIALS FOR SHEAR AND TRUSS BEAM

ENGINEERING MEMORANDUM

TITLE: FINITE ELEMENT MODEL AND WEIGHT COMPARISON OF CANDIDATE MATERIALS FOR SHEAR AND TRUSS BEAM	EM NO: BI-M2-12
	REF:
	DATE: 10 September 1972
AUTHORS: *C. C. Richie* C.C. Richie	APPROVAL: ENGINEERING SYSTEM ENGRG

PROBLEM STATEMENT

For candidate materials, determine optimum structural weights, internal loads, stresses, deflections and member sizes for the shear and truss beam developed on NASA/MSFC Contract NAS 8-27739, "Evaluation of Beryllium for Space Shuttle Components."

RESULTS

Representing typical space shuttle thrust structure components, the shear and truss beam were sized using the SNAP/FSD finite element code which automatically generates fully stressed designs of large bar and shear panel structures. A weight comparison of candidate shear and truss beam materials is summarized in Tables 2 and 3, respectively. Considering one material only, beryllium yields the lightest structure in both cases, however, for both shear and truss beams, the least weight candidate was a combination of boron aluminum for axial elements and beryllium for shear panels. Because of low shear strength, boron aluminum is the heaviest candidate material for the shear beam. Because of high elastic modules and relatively low allowable stresses, beryllium produces the least thrust structure component deflections.

ANALYSIS

1.0 STRUCTURAL DESIGN DATA

Representing typical space shuttle thrust structure components, shear and truss beam geometry, loading and reactions are shown in Figures 1 and 2. As shown below, the shear and truss beam span, depth, loading and reactions are very similar:

	Shear Beam	Truss Beam
Span	360 in.	340 in.
Depth	100 in.	120 in.
Total Vertical Load	783 KIPS	783 KIPS
Total Horizontal Load	165 KIPS	165 KIPS

Differences in loading distribution should have relatively small effect on shear and truss beam weight. Geometric loading and reaction parameters for the shear and truss beam were based on References 1 and 2, respectively. The factor of safety was 1.4 for ultimate strength.

Properties of candidate materials at the 200° F design temperature are presented in Table 1. Candidate materials included beryllium, boron aluminum, 7075-T6 aluminum, 2024-T81 aluminum 64ℓ-4V titanium and AM-350 steel.

2.0 FINITE ELEMENT MODEL

The shear and truss beams were sized using the SNAP/FSD finite element code, which automatically generates fully stressed designs of large bar/shear panel structures. The SNAP/FSD computer output includes optimum structural weights, internal loads, stresses, deflections and member sizes. SNAP/FSD models of the thrust structure components included the following:

	Shear Beam	Truss Beam
Elements		
Bars	97	119
Shear Panels	32	40
Total	129	159
Nodal Points	66	74

Rapid convergence of member stresses and thrust structure component weights was obtained with five design iterations. Excellent numerical accuracy of the solution data was obtained after one iteration of the SNAP/FSD accuracy improvement procedure. External force summations in the X and Y directions indicated maximum residual forces of 3.78 lb and 3.42 lb for the shear and truss beam, respectively. Comparison of external work, W, and strain energy, S, indicated a maximum normalized error, $\frac{S-W}{S}$ of -0.453 x 10^{-5} and -0.204 x 10^{-6}, respectively, for the shear and truss beam. Based on one loading condition and five design iterations, low CPU times of 18 sec and 23 sec per run were obtained for the shear and truss beam, respectively.

Diagrams showing nodal point numbering and element definition for the shear and truss beams are presented in Figures 3 and 4, respectively. The nodal point numbering was selected to reduce the solution stiffness matrix bandwidth and thereby reduce the computer run time. Nodal points and element definitions were selected to provide adequately detailed internal loading distributions and accurate component weights. Minimum axial element areas and shear panel thicknesses were limited to 0.5 in^2 and 0.02 in, respectively.

Allowable stresses of candidate materials for the SNAP/FSD shear and truss beam models are shown in Table 1. It should be noted that structural member sizing in the SNAP/FSD code includes only member force and allowable stress and does not include member instability considerations. Thus, the allowable compressive and shear stress must be selected to provide practical member sizes. To conservatively

account for member instability, SNAP/FSD allowable stresses were selected as follows:

- Tension, $F_t = F_{tu}$
- Compression, $Fc = 2/3 \ Fcy$
- Shear, $Fs = 1/2 \ Fsu$

Detailed member sizing is required for more accurate member allowable stresses.

3.0 WEIGHT COMPARISON

Weight comparison of candidate shear and truss beam materials is shown in Tables 2 and 3, respectively. The non optimum factor of 1.5 conservatively accounts for practical design constraints such as fittings, fasteners, stiffeners, doublers, standard sheet gages and standard structural shapes. Ranking and relative weight penalty for the shear beam was as follows:

Ranking	Candidate Material	Relative Weight Penalty, Percent
1	Boron aluminum bars, Beryllium shear panels	-29
2	Beryllium	0
3	Titanium 6Aℓ-4V	25
4	Aluminum, 7075-T6	43
5	Aluminum, 2024-T81	63
6	Steel, AM-350	109
7	Boron Aluminum	110

Corresponding results for the truss beam were as follows:

Ranking	Candidate Material	Relative Weight Penalty, Percent
1	Boron aluminum bars, Beryllium shear panels	-45
2	Beryllium	0
3	Boron Aluminum	4.2
4	Titanium, 6Aℓ-4V	4.8
5	Aluminum, 7075-T6	29
6	Aluminum, 2024-T81	48
7	Steel, AM-350	81

For both shear and truss beam, the least weight candidate materials were boron aluminum for axial elements and beryllium for shear panels.   Because of low shear strength, boron aluminum is the heaviest candidate material for the shear beam. Weight rankings of other candidate materials depend on strength, density, and structural component.

The effect of candidate materials on the weight distribution between shear/truss beam bars and shear panels is shown in Table 4.   These results indicate the relative importance of shear and axial strength in the shear and truss beams.

Thrust structure component deflections depend on member stress levels and materials elastic modulus.   The effect of candidate materials on maximum limit deflections of the shear and truss beam is presented in Table 5.   Because of high elastic modulus and low allowable stresses, beryllium produces the least thrust structure component deflection.   Conversely, because of high allowable stresses and only fair elastic modulus, titanium produces the greatest shear and truss beam deflections.
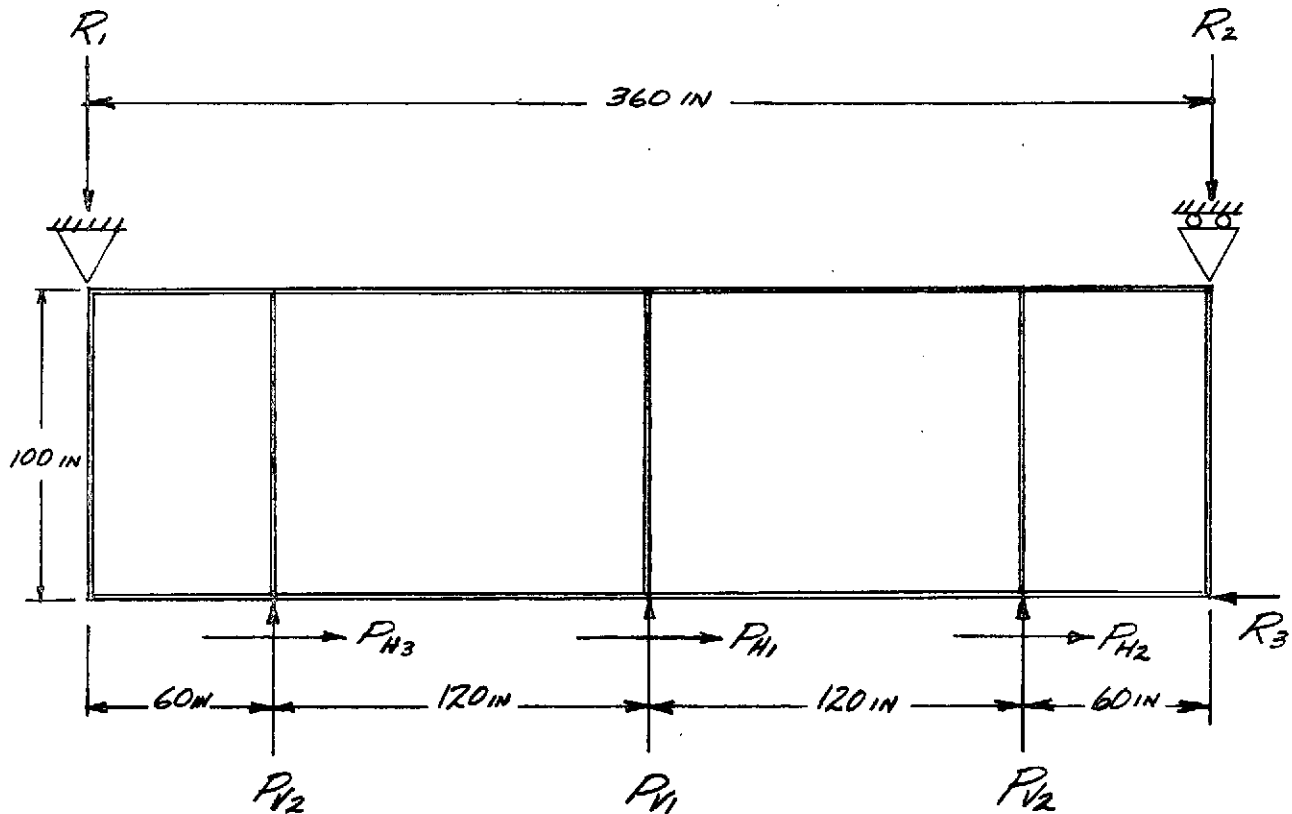
REFERENCES

1. Fuchigami, G.S., "Stress Analysis of Beryllium Shear Beam, SKR 201020,"
    EM No. B1-M2-9, 31 March 1972

2. Fuchigami, G.S., "Stress Analysis of Beryllium Truss Beam, SKR 201017,"
    EM No. B1-M2-8, 9 March 1972

THRUST STRUCTURE SHEAR WEB BEAM
GEOMETRY AND LOADING   FIGURE 1

ULTIMATE LOADS AND REACTIONS

$P_{V1} = 453^K$ $R_1 = 551^K$

$P_{V2} = 330^K$ $R_2 = 562^K$

$P_{H1} = 55^K$ $R_3 = 165^K$

$P_{H2} = 110^K$

$P_{H3} = 0$

THRUST STRUCTURE TRUSS BEAM
GEOMETRY AND LOADING   FIGURE 2

ULTIMATE LOADS AND REACTIONS

P_{V1} = 906 ^{K} R_1 = 489.5 ^{K}

P_{V2} = 330 ^{K} R_2 = 623.5 ^{K}

P_{H1} = 55 ^{K} R_3 = $\dfrac{P_{V1}}{2}$ = 453 ^{K}

P_{H2} = 110 ^{K} R_4 = 165 ^{K}

P_{H3} = 0

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TABLE 1
PROPERTIES OF CANDIDATE MATERIALS AT DESIGN TEMPERATURE

| MATERIAL PROPERTY AT DESIGN TEMPERATURE $T = 200°F$	BERYLLIUM, CROSS-ROLLED	BORON ALUMINUM, UNI-DIRECTIONAL	BORON ALUMINUM, ISOTROPIC	ALUMINUM ALLOY, 7075-T6	ALUMINUM ALLOY, 2024-T81	TITANIUM, 6AZ-4V (S.T.A.)	STEEL, AM-350 (D.A.)
F_{tu}, KSI	74.0	178.2	64.4	71.2	65.3	142.4	158.8
F_{cy}, KSI	53.0	176.4	73.5	66.7	57.3	137.0	134.9
F_{su}, KSI	54.0	11.7	13.6	46.5	38.5	90.0	103.8
E, PSI $\times 10^6$	41.5	26.0	26.0	10.0	10.0	15.4	28.4
ν (2)	0.0625	0.29	0.29	0.33	0.33	0.31	0.32
ρ, LB/IN^3	0.067	0.096	0.096	0.101	0.100	0.160	0.282
F_c, KSI (1)	35.4	117.6	49.0	44.5	38.2	91.3	89.9
F_s, KSI (1)	27.0	5.85	6.80	23.3	19.3	45.0	51.9

NOTES:

(1) SNAP/FSD ALLOWABLE STRESSES: TENSION , $F_t = F_{tu}$ (2) AT ROOM

COMPRESSION , $F_c = 2/3 F_{cy}$ TEMPERATURE

SHEAR , $F_s = 1/2 F_{su}$

THRUST STRUCTURE SHEAR WEB BEAM
SNAP/FSD FINITE ELEMENT MODEL
NODAL POINT DIAGRAM AND LOADING

FIGURE 3

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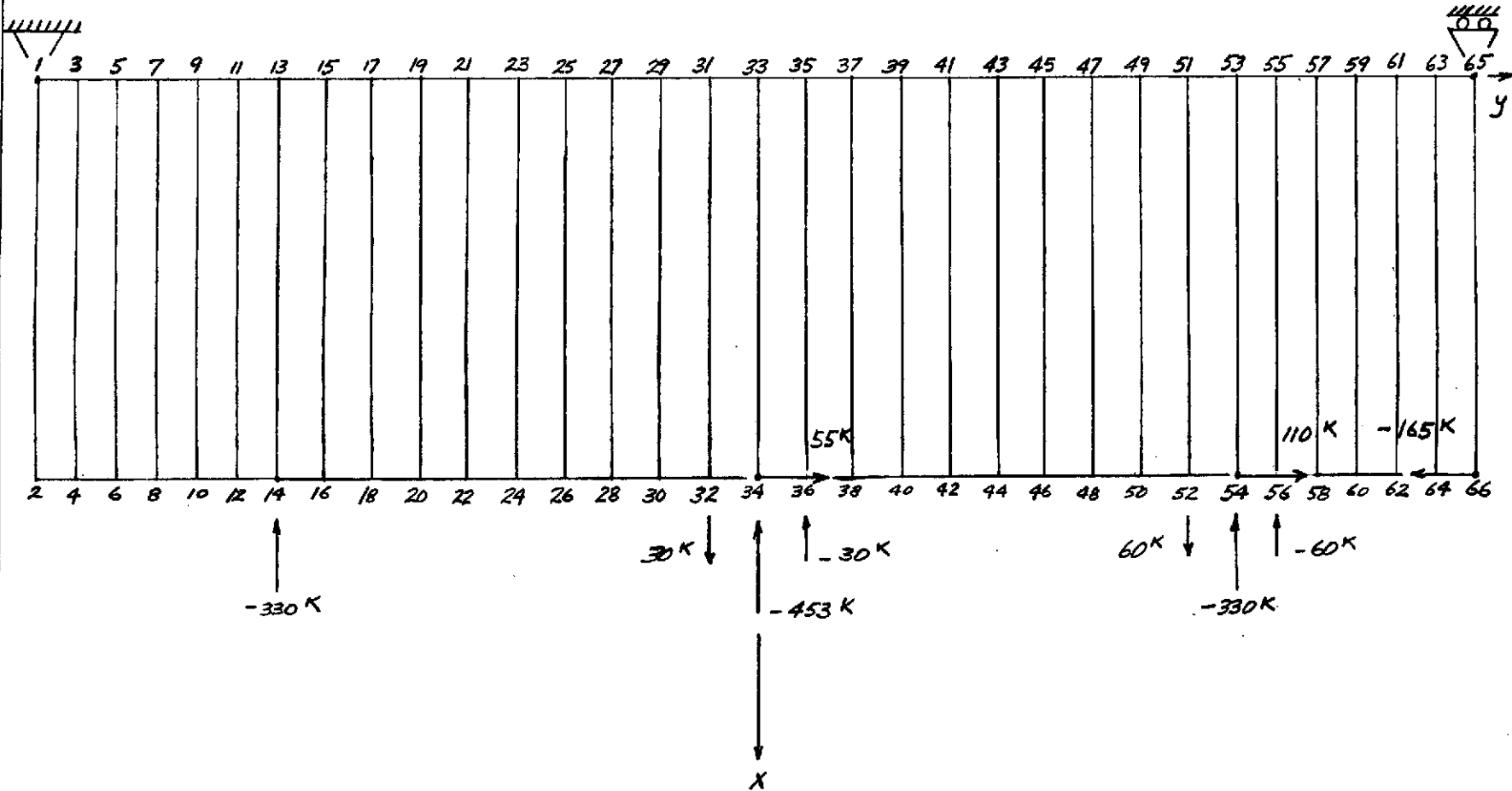
Prepared by: C. C. Richie
Checked by:
Approved by:

Date
Date
Date

LOCKHEED MISSILES & SPACE COMPANY, INC.

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THRUST STRUCTURE TRUSS BEAM
SNAP/FSD FINITE ELEMENT MODEL
NODAL POINT AND LOADING DIAGRAM

FIGURE 4
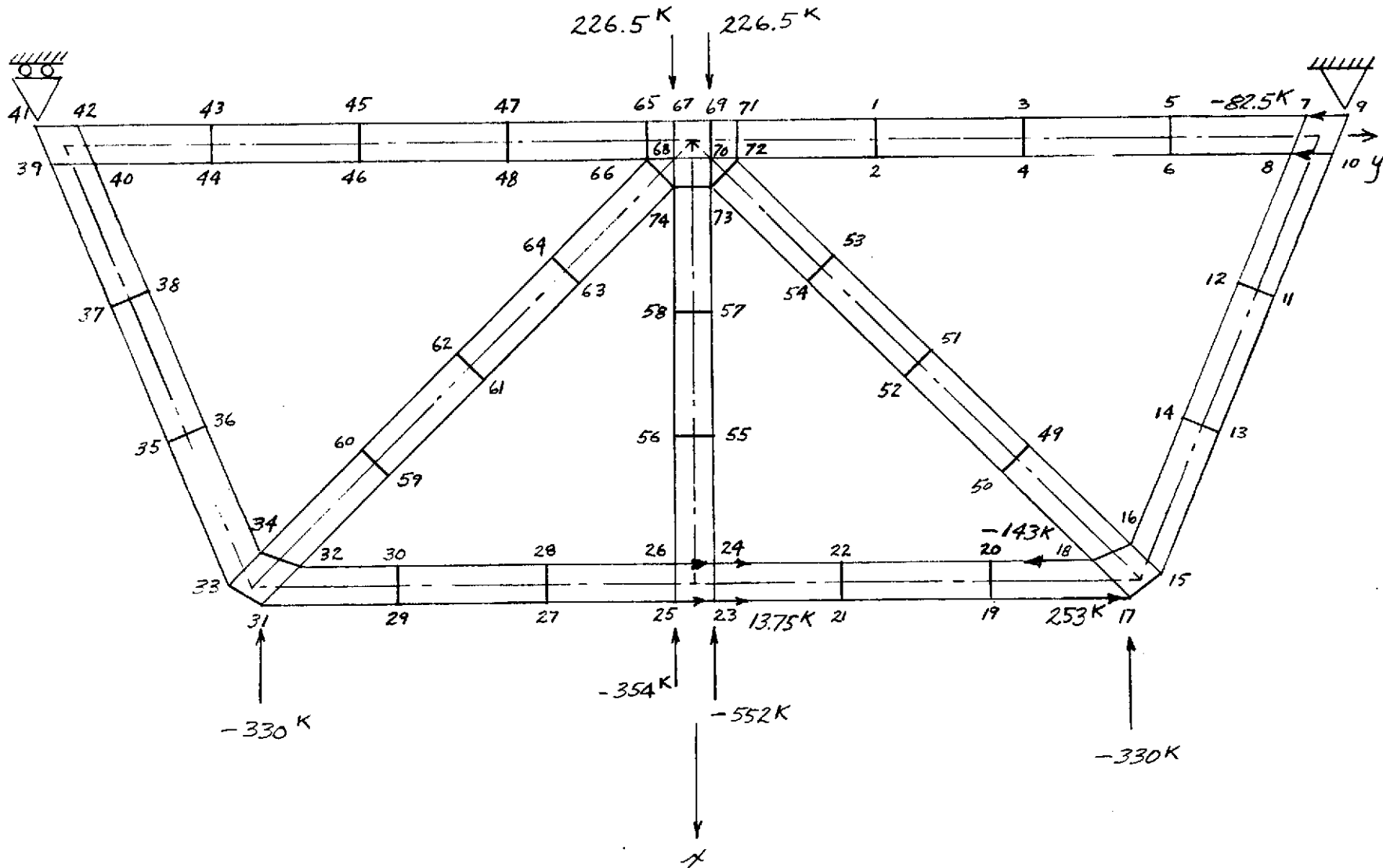
TABLE 2
WEIGHT COMPARISON OF CANDIDATE SHEAR BEAM MATERIALS

CANDIDATE MATERIALS	IDEAL SNAP/FSD MODEL WEIGHT (2)(3)			ACTUAL SHEAR BEAM STRUCTURAL WEIGHT (1)			RELATIVE SHEAR BEAM STRUCTURAL WEIGHT		
	BARS, LB	PANELS, LB	TOTAL, LB	BARS, LB	PANELS, LB	TOTAL, LB	BARS, LB	PANELS, LB	TOTAL, LB
BERYLLIUM	705.32	297.33	1002.65	1057.98	446.00	1,503.98	1.0	1.0	1.0
BORON - ALUMINUM	417.50	1,691.58	2,109.08	626.25	2,537.37	3,163.62	0.5919	5.6892	2.1035
ALUMINUM, 2024 - T81	1,021.99	620.83	1,642.82	1,532.99	931.25	2,464.23	1.4489	2.0880	1.638
ALUMINUM, 7075 - T6	917.39	519.39	1,436.78	1,376.09	779.09	2,155.17	1.3006	1.7468	1.4329
TITANIUM, 6Al - 4V (STA.)	826.64	426.03	1,252.66	1,239.96	639.05	1,878.99	1.1720	1.4328	1.249
STEEL, AM-350 (DA)	1,445.63	651.04	2,096.68	2,168.45	976.56	3,145.02	2.0496	2.1896	2.091
BORON ALUMINUM BARS BERYLLIUM SHEAR PANELS	417.50	297.33	714.83	626.25	445.99	1,072.24	0.5919	1.0	0.7129

NOTES:

(1) NON - OPTIMUM FACTOR, NOF = 1.5

(2) MINIMUM BAR AREA, $A_{min} = 0.5 \text{ in}^2$

(3) MINIMUM PANEL THICKNESS, $t_{min} = 0.02 \text{ IN}$

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TABLE 3
WEIGHT COMPARISON OF CANDIDATE TRUSS BEAM MATERIALS

CANDIDATE MATERIALS	IDEAL SNAP/FSD MODEL WEIGHT (2)(3)			ACTUAL TRUSS BEAM STRUCTURAL WEIGHT (1)			RELATIVE TRUSS BEAM STRUCTURAL WEIGHT		
	BARS, LB	PANELS, LB	TOTAL, LB	BARS, LB	PANELS, LB	TOTAL, LB	BARS, LB	PANELS, LB	TOTAL, LB
BERYLLIUM	877.09	65.385	942.47	1,315.62	98.078	1,413.71	1.0	1.0	1.0
BORON - ALUMINUM	413.61	568.81	982.41	620.42	853.22	1,473.62	0.4715	8.6993	1.0423
ALUMINUM, 2024-T81	1,258.71	131.52	1,390.23	1,888.07	197.28	2,085.35	1.4351	2.0114	1.4750
ALUMINUM, 7075-T6	1,110.76	108.52	1,219.27	1,666.14	162.78	1,828.91	1.2664	1.6597	1.2936
TITANIUM, 6Al-4V (STA)	881.37	106.64	988.01	1,322.06	159.96	1,482.02	1.0048	1.6309	1.0483
STEEL, AM-350 (DA)	1,547.18	162.75	1,709.93	2,320.77	244.13	2,564.90	1.7651	2.4891	1.8143
BORON ALUMINUM BARS BERYLLIUM SHEAR PANELS	413.73	100.21	513.94	620.60	150.32	770.91	0.4717	1.5326	0.5453

NOTES:

(1) NON-OPTIMUM FACTOR, NOF = 1.5

(2) MINIMUM BAR AREA, A_{min} = 0.5 IN^2

(3) MINIMUM PANEL THICKNESS, t_{min} = 0.02 IN

TABLE 4

EFFECT OF CANDIDATE MATERIALS ON THE WEIGHT DISTRIBUTION BETWEEN SHEAR/TRUSS BEAM BARS AND SHEAR PANELS

CANDIDATE MATERIAL	WEIGHT DISTRIBUTION, PERCENT			
	SHEAR BEAM		TRUSS BEAM	
	BARS	SHEAR PANELS	BARS	SHEAR PANELS
BERYLLIUM	70.34	29.65	93.06	6.94
BORON-ALUMINUM	19.79	80.20	42.10	57.90
ALUMINUM, 2024-T81	62.21	37.79	90.54	9.46
ALUMINUM, 7075-T6	63.85	36.15	91.10	8.90
TITANIUM, 6Al-4V	65.99	34.01	89.21	10.79
STEEL, AM-350	68.95	31.05	90.48	9.52
BORON ALUMINUM BARS, BERYLLIUM SHEAR PANELS	58.40	41.59	80.50	19.50

NOTES:

(1) BASED ON SNAP/FSD FINITE ELEMENT MODEL

(2) MINIMUM BAR AREA, $A_{min} = 0.5$ in^2

(3) " PANEL THICKNESS, $t_{min} = 0.02$ IN

TABLE 5

EFFECT OF CANDIDATE MATERIALS ON MAXIMUM LIMIT DEFLECTION OF TRUSS AND SHEAR BEAM

CANDIDATE MATERIAL	MAXIMUM LIMIT DEFLECTION, IN (1) (2)	
	SHEAR BEAM (3)	TRUSS BEAM (4)
BERYLLIUM	− 0.54356	− 0.65927
BORON-ALUMINUM	− 1.72374	− 2.70257
ALUMINUM, 2024-T81	− 2.13021	− 2.62977
ALUMINUM, 7075-T6	− 2.45298	− 2.96185
TITANIUM, 6Aℓ-4V	− 3.16136	− 3.84607
STEEL, AM-350	− 1.85007	− 2.18471
BORON ALUMINUM BARS, BERYLLIUM SHEAR PANELS	− 1.81471	− 2.73186

NOTES:

(1) BASED ON SNAP/FSD FINITE ELEMENT MODEL

(2) FACTOR OF SAFETY , F.S. = 1.4

(3) OCCURS AT NODAL POINT NO. 34

(4) OCCURS AT NODAL POINT NO 23

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